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SMALL DROPLET MEASURING TECHNIQUE

Phase I Technical Report

B. J. Matthews

R. F. Wuerker

D. T. Harrje

TRW Systems
One Space Park, Redondo Beach, California

TECHNICAL REPORT AFRPL-TR-67-295

February 1968

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Air Force Rocket Propulsion Laboratory
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Air Force Systems Command
United States Air Force

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FOREWORD

This Phase I Technical Report was prepared for the Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California. The report was prepared by the Power Systems Division of TRW Systems Group, TRW, Inc., and has been assigned TRW Report Number 4768.67-006. It is submitted in accordance with the provisions of Contract F04611-67-C-0105.

The Phase I effort was conducted during the period 1 May 1967 through 30 August 1967. Lt. C. J. Abbe served as Air Force Program Monitor. The TRW Program Manager was Mr. B. J. Matthews. Dr. R. F. Wuerker of TRW's Physical Electronics Laboratory directed the holography research and experimentation. A significant portion of the literature search together with the spark photographic studies was accomplished under a TRW subcontract to Princeton University. This work was directed by Mr. D. T. Harrje of the University's Guggenheim Laboratories.

Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

CHARLES J. ABBE, 1st Lt. USAF
AFRPL Program Monitor

SMALL DROPLET MEASURING TECHNIQUE

Phase I Technical Report

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ABSTRACT

A study and experimental program is being conducted which involves the detection and analysis of size distributions of droplets associated with the injection process in liquid propellant rocket engines. Program objectives are to: (1) Determine, through a review of the literature, applicable methods of detecting and recording rocket injector droplet spray distributions; (2) Demonstrate feasibility of experimental techniques selected from the literature using cold flow propellant simulants; and, (3) Improve the methods of data reduction such that large quantities of droplet data may be reduced economically.

The program is divided into two phases. Phase I is primarily devoted to a review of the literature for applicable spray measuring and data reduction techniques. A limited amount of experimentation is included in this phase to assist in the evaluation of the various techniques and methods under consideration. Phase II is concerned with the design, assembly and feasibility demonstration of the droplet detection techniques selected as a result of the Phase I effort. Development of a compatible droplet data reduction method will comprise an integral portion of the second phase effort.

This report reviews the Phase I activities during the period 1 May through 30 August 1967. Candidate droplet detection techniques and data reduction methods are discussed in context with program objectives and evaluation criteria. Particular attention is given to the application of holography to droplet detection and the results of preliminary holographic experiments are indicated. Conclusions are presented based upon the results of the literature review and the Phase I experimentation. A program plan for the second phase is outlined.

ACKNOWLEDGEMENT

The authors wish to acknowledge the significant assistance of various individuals, both at TRW Systems and at the Guggenheim Laboratories of Princeton University, in the conduct of the Phase I effort of the Small Droplet Measuring Technique Program.

Valuable contributions in the field of pulsed laser holography were made by R. E. Brooks, L. O. Heflinger and C. Knox of TRW's Physical Electronics Laboratory.

At Princeton University, the literature search was made under the direction of Mr. M. H. Smith. Computer program formulation was accomplished by Mr. L. L. Hoffman. Engineering development on the Particle Analyzer mechanism was done by Mr. V. Warshaw with consultation from Mr. J. B. Cooper in the field of electronics.

CONTENTS

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1. INTRODUCTION

A knowledge of the drop size distribution within a liquid propellant rocket engine is extremely valuable from the standpoint of understanding the combustion phenomena. A number of experimental and theoretical investigations emphasize the importance of droplet size and distribution with regard to performance and stability. Consequently, many studies of the atomization and vaporization processes have been conducted. In spite of these numerous studies, the state of our knowledge is such that it is still difficult to predict rates of vaporization of sprays for a given type of injector, propellant combination and combinations of operating conditions. This is largely due to incomplete information regarding drop size distributions from the various bipropellant injectors currently in use.

The atomization of a liquid jet into drops is a complex process in which interrelated aerodynamic and hydrodynamic effects come into play. The action of gas friction and pressure causes the deformation of drops and ligaments which subsequently break up in the relative airflow. It seems generally agreed that this always occurs, regardless of whether the liquid enters still air at high speed, or whether a low speed jet interacts with a faster gas flow. Studies have resulted in the experimental confirmation of theoretical relations that predict the life history of single drops of various liquids, subjected to an atmosphere of various temperatures, pressures, and velocities. The accuracy of the predictions for the sizes studied (500 to 5000 microns diameter) was nearly as great as the accuracy with which the physical properties are known. Yet, in the study of small drop (10 to 100 microns diameter) breakup, there appear to be substantial gaps in our knowledge.

In an effort to gain additional understanding and knowledge in the critical area of small drop formulation, a two-phase program "Small Droplet Measuring Technique", was initiated under the sponsorship of the Air Force Rocket Propulsion Laboratory. This report contains a description of the study and experimental activities accomplished during Phase I of the program. A summary of these activities is presented in Section 2.

A significant portion of the study effort was devoted to a review of the literature for applicable small droplet detection methods. The results of the literature survey are discussed in Section 3. The supporting experimental work is reported in Section 4. Conclusions are drawn from the work accomplished in this phase of the program and recommendations are made regarding the activities to be conducted during Phase II. The recommendations for Phase II are in the form of a general outline as prescribed by contractual requirements.

2. SUMMARY OF TECHNICAL ACTIVITIES

2.1 GENERAL

Phase I of the Small Droplet Measuring Technique Program was initiated on 1 May 1967, and concluded on 30 August 1967. During this 4-month period, the technical effort was divided into two main tasks. The first task was to review and evaluate candidate methods of detecting and recording size distributions of droplets associated with liquid rocket engines. The second task was the conduct of experimental studies designed to augment the literature search and assist in the evaluation process.

2.2 LITERATURE SURVEY

Literature survey activities were subdivided between TRW Systems and Princeton University. A subcontract was issued to Princeton authorizing a rather broad review and evaluation of the various small droplet detection methods excluding only laser holography. TRW Systems assumed responsibility for reviewing published information available on laser holography and related topics as they might apply to small droplet detection.

Midway through Phase I, an Air Force/TRW program review resulted in more emphasis being placed upon experimental efforts. Correspondingly, the scope of the literature survey was narrowed and consideration was given to seven basic droplet detection techniques:

- Electrical and Electronic Systems
- Deposition and Collection Methods
- Light Scattering Techniques
- Fluorescent Photography
- Streak Photography
- Spark Shadowgraphs
- Laser Holography

In the process of executing the literature survey, several hundred documents were cataloged. Over 100 of the more pertinent documents were abstracted. A total of 61 were considered as major references in relation to this program and appear in a bibliography at the end of this report.

The major references were reviewed in depth. As part of the review, an assessment of the respective technique was made. This assessment or evaluation was based upon engineering judgement, prior first-hand experience, and a set of criteria imposed by contractual requirements. The criteria are presented in Section 3 of this report.

Another facet of the literature survey was a review of possible electronic data reduction and processing techniques for small droplet information. In this respect, the "flying-spot" scanner is reviewed. This information, together with a synopsis of each of the seven droplet detection methods is presented in Section 3.

2.3 EXPERIMENTAL STUDIES

The experimental studies initiated during Phase I were designed to support the evaluation of the various techniques determined from the literature. The work was divided into three parts: 1) Laser holographic experiments, 2) Spark photographic studies, and 3) Development of a computer-based fiber optics data reduction technique.

The pulsed ruby laser holographic experiments were conducted by TRW Systems. A series of 36 holograms was made using like-on-like, impinging stream injector elements flowing distilled water. These tests demonstrated the feasibility of applying pulsed laser holography to small droplet detection.

Consideration was also given to the possibility of developing a holographic technique for distinguishing between two colors. The object was to provide a method of determining local mixture ratio conditions using simulated propellants. Experimental efforts were not completed during Phase I. Work was initiated, however, and a method of accomplishing this objective is presented.

A portion of the subcontract to Princeton provided for demonstration of an improved spark photographic system and the initiation of work on a computer-based, fiber optics data reduction system. The improved spark photographic system incorporated an increased spark (light) intensity level and a Kerr cell shutter to effect 50-nanosecond light pulses.

The spark photographic optical system was readied for the test program. The required Kerr cell was not available, however, and consequently the test series had to be postponed.

The electronic data reduction system being developed by Princeton is nearing completion. A mechanical scanning device was fabricated to accommodate the 10-micron fiber optics array used in the sensing of droplet images on a photographic negative. Difficulties have been experienced in the assembly of the delicate glass fibers; however, continued experimentation has led to a bonding technique which appears feasible.

A computer program was devised to accept data input from the fiber optics scanning mechanism and provide suitable droplet data reduction. The computer program was verified using a set of cards containing simulated droplet data.

3. LITERATURE SURVEY

3.1 INTRODUCTION

The literature on droplet spray analysis is extremely large and diversified. It extends, for instance, from aerosol sprays to liquid rockets to meteorology. A complete review of all aspects of droplet spray literature during Phase I was, of course, beyond the program scope.

The literature survey conducted during Phase I was directed toward two areas of primary interest. The first was a review of applicable state-of-the-art methods of droplet detection. By definition, "applicable" droplet detection methods are those techniques which might be compatible with the program evaluation criteria cited in Section 3.2 of this report. State of the art implies that feasibility of a given technique has been demonstrated and reported in the literature or — as in the case of pulsed laser holography — sufficient experimental work was accomplished during Phase I to permit evaluation.

A second area of interest centered about reviewing the literature for methods of automated droplet data reduction and processing. Any method considered would, of course, have to be compatible with the primary droplet detection system and also be rapid and economical. Comment on this aspect of the literature is provided in Section 3.3.1.

A total of six basic techniques (excluding laser holography) of detecting and recording droplets were considered as a result of the general literature survey. These techniques are:

- Electrical and Electronic Systems
- Deposition and Collection Methods
- Light Scattering Techniques
- Fluorescent Photography
- Streak Photography
- Spark Shadowgraphs

Each technique is subsequently treated in summary form in context with the program evaluation criteria.

The employment of laser technology to the problem of detecting droplet spray distributions was of specific interest during Phase I. A separate literature survey was undertaken to explore related work being conducted in this specialized field. For this reason, and because the technique appears to offer considerable promise, a more detailed review is presented. This information is contained in Section 3.4.

3.2 EVALUATION CRITERIA

Specific long-term objectives were stipulated at the start of the program. These specific objectives, which become evaluation criteria when reviewing candidate droplet detection techniques, state that applicable droplet detection methods should be:

- Able to measure droplets having a 10-micron to 500-micron diameter with a 10 percent maximum error at the low-size range
- Able to measure the distribution at any location across a typical 6-inch diameter injector, as well as any position axially from the injector face onward
- Able to make the measurements specified above at droplet flux levels typical of engines operating at 3000 psia chamber pressure (order of magnitude 10^{11} drops/in^2 sec)
- Able to distinguish between fuel simulant droplets and oxidizer simulant droplets (cold flow) when both are flowing simultaneously
- Potentially applicable to rocket engine firings.

In Reference 1, J. D. Lewis has set forth some ideal droplet detection system requirements. In part, he suggests that the ideal detection and recording system should:

- Not disturb the spray pattern or atomization mechanism
- Be able to sample at various times and at various points in a given space
- Not be restrictive as to the choice of liquids employed
- Not be restrictive with regard to ambient test conditions
- Apply to all ranges of flow, velocity and dispersion
- Provide a permanent record

To the preceding lists, one might add the consideration of initial and operating costs. For instance, if these costs are prohibitive there is little merit to the system regardless of other salient features. Unfortunately, there is little in the literature indicating absolute or relative cost of one system versus another. If laboratory studies of limited scope are to be made, an extremely sophisticated and costly droplet data acquisition system may not be justifiable. Conversely, the ultimate application of a sophisticated system to production injector acceptance test operations, or to an elaborate and continuing combustion stability program, may warrant a significant investment in equipment.

A detailed assessment of the initial and operating cost aspects for the various techniques under consideration is beyond the scope of this literature review. However, a summary chart presented at the conclusion of this section includes an estimate of the relative costs associated with each system. This estimate is done with the assignment of a "relative cost factor." The relative cost factor was estimated by comparing each technique with the spark photographic method. This method (assigned a base number of 1.0) was arbitrarily selected as a well established and convenient reference. The numbers presented are considered only as a guide in the comparison of one system to another. Certainly all technical and financial factors that may be involved must be carefully considered for each individual application.

3.3 GENERAL LITERATURE SURVEY

3.3.1 Electrical and Electronic Systems

The first criterion of droplet measurements from 10 to 500 micron diameter would appear to be met by the droplet mobility measuring system described in the Whitby paper (Reference 2). This system employs a probe technique (the droplets pass through a device in which an electrical field has been established) and is utilized to measure aerosol spray droplets in the order of 1 micron or less in diameter. The measurement of aerosol-size droplets depends on the ability to reduce background currents to less than 10^{-14} amperes. The significance of these values is that this technique has been applied to these extremely small droplets where charge limitations would be expected to pose the major problem -- hence, the use of this approach to measure 10 micron diameter droplets should be less critical in such a "laboratory" environment. Questions remain, however, as to the achievement of such favorable signal-to-noise ratios in a simulated rocket environment. Also, this probing technique cannot be considered as ultimately appropriate to the hot firing situation.

Concerning the problem of differentiation between fuel and oxidizer particles, this has been attempted in Reference 3, although no final conclusions could be reached due to limitations of the auxiliary electronic apparatus. Further, the probe would interfere with the local droplet samples. This is particularly the case for the very small droplets which would be discriminated against due to inertial effects.

The Gardiner paper (Reference 4) cites extremely high sampling rates (200,000 drops per minute).* The same disadvantages are present here as in the Whitby paper. It seems that the removal of the liquid from the charge wire is the greatest single difficulty. Such collection influences the characteristics of the probe. If we use the design point of 10^{11} drop/in^2 sec., and assume the probe only takes up .01 in^2, we find that the high sampling rates quoted above fall short of the requirement by approximately 7 orders of magnitude. Thus, achieving this requirement would appear doubtful.

Fisher and Rojec present their work in developing and demonstrating an electronic probe to measure drop size distributions in Reference 5. They developed a system employing an electrometer probe to intercept charged moving droplets. The extent of the charge exchanged with a given droplet and the probe was related to the size of the droplet. Droplet diameters of less than 200 microns were successfully measured. It was also postulated that droplet diameters of less than 100 microns could be measured. However, this type of probing apparatus would certainly not be compatible with actual rocket combustion environments or cold flow studies near the injector.

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* This is for charged particles falling on a detecting wire.

In summary, the application of existing electronic systems to droplet detection offers the potential of measuring very small droplet diameters (down to 1 micron) and the development of high sampling rates. The ultimate use of these techniques in the detection of burning droplets in a rocket engine combustion environment does not appear feasible.

Another factor in the analysis of droplet sprays is the final data reduction. Included in this category are the electronic analyzers (References 6 and 7). Much literature references the Mullard Automatic Counter and Sizer. This is a "flying-spot" scanner with a resolution of 1000 points across the tube. This technique cannot cover a 35 mm film frame to the desired accuracy, so that small sections must be done by photographic enlargement. The scanner is fast; however, resolution is a problem with this type of device.

The errors inherent in such scanners are an accumulation of error. For example, noise in the electronic beam deflector can shift an entire line or even a set of lines since the positioning circuitry is essentially an integrator. In a mechanical lead screw device, noise (dust) provides only a momentary error which would be corrected as the noise source was passed. The Mullard Scanner does have a useful design feature (adjacent line storage) which allows some logical decisions to be made on droplet slope. By this means, noise effects are reduced. If the resolution (raster) could be increased 3.5 times, 10 micron droplets could be measured on a 35 mm frame. This would require a minimum raster of 3500 points across the scanner tube. This figure appears to be near the limits of technology at this time (a 2000 point raster was attained for bubble chamber analysis within the last 18 months).

Although the flying-spot scanner would not cover a 35 mm frame to the required accuracy, it is used very effectively on smaller samples. A very good example of the use of such a device for high volume analysis is found in a paper by Ledley and Ruddle (Reference 8). The paper presents a method of examining individual chromosomes for abnormalities.

3.3.2 Deposition and Collection Methods

One of the most accurate methods of size determination is a method of examining the actual droplets at one's leisure. By simply collecting the droplets on a slide or by freezing them, the droplets may be examined by precision microscopes without concern about the optical systems required for photography of droplets. This microscopic inspection is a manual operation and certainly not suited for large numbers of droplets. Reference 3 cites the use of sieves to rapidly classify droplet sizes; however, the lack of availability of sieves smaller than 37 microns necessitated a return to the microscope. A good review of this subject may be found in Chapter 4 of Reference 9, as well as the references cited in Reference 3.

The basic difficulties are ones of sampling (mechanical shutters have been used), choice of simulants (wax is often employed) and possibility of coalescence of liquid droplets during the freezing period. These methods, although accurate, do not satisfy most of the program objectives. Specifically, the technique is not applicable to rocket engine firings; coalescence becomes a major problem at high flux densities, and the final frozen droplets are a strong function of the freezing process and hence cannot mirror the changing conditions in a real combustion environment.

3.3.3 Light Scattering Techniques

The Battelle report, cited in the preceding paragraph, has a section in Chapter 4 on light scattering and absorption. At one time, there was some hope that measurement of scattered light would provide particle size distribution. Actually, the resulting diffraction patterns yield an average D_{32} (Sauter Mean Diameter) for the droplet field. This is sufficient for steady-state combustion studies but fails to meet the small droplet size criteria of the present program. If only a D_{32} value is determined from the spray, whether from individual droplet counts or through the use of the light scattering technique, the importance of the small droplets can be easily overlooked, as stated in Reference 10.

Further limitations of the light scattering technique in regard to its applicability to the analysis of rocket injection sprays is its sensitivity to change in refractive index of the surrounding medium. It has already been shown in hot firing engine tests at Princeton University that almost insurmountable difficulties exist in separating the refractive scattering from the diffractive scattering with conventional light sources. The former is due to random fluctuations in the gas movement surrounding the spray. For the same reason, the extension of the light scattering technqiue to rapidly vaporized propellants is deemed questionable.

3.3.4 Fluorescent Photography

A technique which would appear interesting is fluorescent photography of the droplets. Reference 11 presents the basic techniques of fluorescent droplet photography using a Q-switched laser as a light source.

By the use of a planar slab of excitation radiation, it is possible to sample at precisely known positions in the droplet spray. An advantage over some techniques is the possibility of differentiation between fuel and oxidizer through the use of color film (the two liquids could be made to fluoresce in different spectral regions). The problems involved in reliably interpreting color gradation, and in achieving data reproducibility, would have to be carefully studied. Another unknown factor is the effect of adding dyes to the propellants. This could be unnecessary if an excitation source could be found to cause fluorescence in a fuel and oxidizer (providing that it is possible for them to fluoresce).

One problem area did become apparent in the work reported in Reference 12. It was found that when the full intensity (flux about .5 joule over a 50 nsec. duration) of the laser light reached a suspended drop, there was evidence of droplet destruction. At lower intensities, vapor was generated on the sides of droplets that were laser illuminated. This of course would violate the first principle cited by J. D. Lewis in Reference 1. To make use of this technique in a rocket environment would appear to require a rather extensive and perhaps costly study of fluorescent properties of liquid propellants and additives as well as the photographic techniques.

3.3.5 Streak Photography

Streak photographs of droplet sprays are obtained by moving film at right angles to a slit (the slit lies along the flow axis), and recording both size and velocity of droplets as streaks of varying thickness and inclination on the film. Difficulties arise in this technique in the detection of a single large droplet versus groups of smaller drops passing over the slit.

In the streak record provided by a moving droplet, the center is more dense than the edges, making it even more difficult to analyze size. This is especially true if the droplet is changing shape with time. Problems of depth of field and whether or not the lighting is coherent can further complicate the analysis of such droplet streak records. In brief, such records can only be looked upon as qualitative records of droplet size distributions with only remote possibilities of deriving size-versus-position data for representative droplets and even then not droplets in the 10 micron size range.

3.3.6 Spark Shadowgraphs

It has been known for years that a capacitor discharged through an arc produces a short-duration, high-intensity light. This light source has been used for recording droplets on film with only a small amount of movement of the droplet during exposure. A camera is used to record the light so that there is a definite limit to the volume which may be sampled.

Droplet diameters as small as 10 microns have been measured at Princeton (Reference 10) using spark light sources. Droplet velocities are difficult to measure except by successive exposures on the same film frame. This presents a very difficult problem in the analysis of the resulting photograph.

The intensities and durations of light pulses from sparks are such that fast films must be used with very active developers. The image will usually be degraded under these conditions. The light sources now being used are lasers which provide very high intensity light over extremely short durations. This, of course, offers the possibility of overcoming some of the previously mentioned limitations to making droplet shadowgraphs. This higher intensity light source becomes especially important in a combustor environment where it is necessary to overcome the combustion light in order to properly illuminate the droplets under study.

3.4 LASER HOLOGRAPHY

The literature survey on holography covered the period from the year 1939 to the present. The task was greatly facilitated by a number of excellent surveys already completed, the best of which was by the Physical Society of Japan on behalf of their members. This very complete survey is a bound volume containing 35 selected reprints of the most important papers on holography, along with a listing (by year) of a total of 235 papers. In this country an excellent survey was conducted by R. P. Chambers and J. S. Courtney-Pratt for the Bell Telephone System as their Monograph 5185. This survey was also published in the Journal of the SMPTE: Volume 75, pp. 373-435, April 1966; Vol. 75, pp. 759-809, August, 1966; and Vol. 76, pp. 392-395, April 1967. This search lists 420 different articles and presents abstracts of most all the listed papers.

Another compilation was obtained from England: The Atomic Weapons Research Establishment, Aldermaston, England. It was compiled by L. Corvett and contains a listing of 208 unclassified papers, and gives papers published on the continent. Other surveys were reviewed, but were essentially redundant to the three cited above; for example, one by Tomiyasu, IEEE Journal of Quantum Electronics, Vol. QE-2, No. 6, June, 1966.

A computer survey was made (at TRW request) by the Documentation Center for Scientific and Technical Information, Cameron Station, Alexandria, Virginia. The first level of the search was keyed to the words holograms, holography, and lasers. The second level of the search included aerosols, combustion, droplets, fog, mist, particles, and rocket motors. The third level of the search encompassed measurements, measuring devices, test equipment, and tests. The search served as an interrogation of the classified and unclassified government literature. It uncovered no materials which had not been listed in the above cited unclassified surveys. The search did serve to make available the means of obtaining government reports. Of importance were the reports published by the University of Michigan (Ann Arbor), the University of Texas (Austin) and Technical Operations (Burlington, Mass.). A similar survey was requested from NASA, but this has not yet been received.

The survey has resulted in a bibliography of 336 different papers on the subject of holography and holographic techniques. The assembled bibliography is in a card file at TRW Systems and will be updated periodically.

The question of the application of holography to the measurement of fogs, sprays, etc., and the resolution of the technique is not answered clearly in any of the papers. One cannot cite a single paper which definitely claims specific tests of resolution. Part of the problem enters with the fact that the resolution is limited by the wavelength of light itself. When one attempts to make measurements in this range, one is beset with difficulties. The other problem is that of coherent light itself and the fact (still not appreciated by all) that it limits resolution over that of incoherent sources. Starting with Gabor's basic papers, there are 28 papers and reports which deal with the measurement of small distances and particles via holographic technique. These are listed in the bibliography under Holography.

A paper by Kirkpatrick, et al, (Reference 13) describes the reconstruction of 10 micron lines from holograms recorded with filtered light from a zirconium arc. This paper is important in that it was written before the advent of the laser. The filtered zirconium system meant that exposure times were of the order of 10 minutes so the paper was only of pedagogic interest. There are 14 papers listed by the group at Technical Operations Research, Burlington, Massachusetts, which deal with Gabor or "line-holograms" made with the pulsed ruby laser. In essence, these papers tout the virtues of holography to deal with particles distributed over large volumes. They also report on the reconstruction of particles of the order of 30 micron size, but do not make a specific claim at the ability to approach the ultimate in resolution. The Technical Operations approach also uses lenses in the recording of their holograms which aids in the retrieving of resolution, but also limits the recorded volume.

The paper by Denisyuk of Russia (Reference 14) reported upon the reconstruction of 10 micron lines from holograms made with the filtered radiation from a mercury vapor lamp. The paper also contains a general discussion of the effect of emulsion thickness on the reconstructed images.

Of the many papers and books published by G. W. Stroke, only one paper (Reference 15) and his book (Reference 16) are cited in the present survey. The paper shows the reconstruction of a fly's wing, but does not cite any values of measured resolution. The book is equally vague on the subject. Of the many papers written by E. N. Leith and group, two deal with the subject of holographic microscopy and resolution (References 17 and 18). Like Stroke's papers, both discuss the theory of the process, what might be expected, the role of the film, etc., but neither gives much in the line of experimental evidence. Again, the difficulty of the measurement is one of the reasons for making the test, particularly when all the aspects of this new field are just being discovered. The paper (Reference 17) presented at the Optical and Electro-Optical Information Processing Symposium showed the reconstruction of bars separated by 7-10 microns.

Of the work on microscopy at TRW Systems, two papers are cited. One has been published in the open literature (Reference 19) and described the reconstruction of small plankton from Gabor holograms made with a Q-switched ruby laser illuminator. The paper emphasized the depth of field capabilities of holography, but like the other ones cited, did not make a statement on resolution. The final report under contract AF 33(615)-1035 (Reference 20) contains a long discussion on holographic microscopy and gives examples of reconstructions of objects of the order of 3 microns in size from Gabor holograms. The results have not as yet been published in the open literature.

The other work at TRW Systems with the two-beam holocamera described in this report cited the achievement of resolution to 20 microns (Reference 21). One of the problems which one has with coherent light is the granularity effect which is also a diffraction phenomena and within which phenomena can hide. Reference 20 discusses this problem in some detail.

The work at the University of Texas (References 22-25) and at the American Optical Company (Reference 26) has been concerned with the aiding of a conventional microscopy with a hologram. In this way, one gains a little over the depth of field of the microscope objective as well as being able to make interferometric measurements. Resolution is then limited by the objective lens (which is close to ultimate) rather than by the holographic process. Resolution cited by Carter and Van Lichten has been of the order of 1 micron or slightly less and is limited by the numerical aperture of the observing lens.

In brief, the problem and question of resolution has not been completely settled. First, there is the problem of coherent light and the "everywhere-diffraction problem" or "granularity effect" which this creates. Next, there is the numerical aperture or ratio of the limiting aperture of the hologram and distance of the event. Finally, there is the problem of testing and proving resolution. In general, the results to date are encouraging in the sense that resolution of the order of 10 microns has been found. To test to higher levels of resolution demands the clear formulation of a need.

On the problem of transmission through fogs and mists, none of the available literature has addressed itself to this question. The group at Technical Operations has centered its work around a device that measures particles in fogs (Reference 27). In general, their work has been concerned with rather static phenomena. No comparisons have been made of holograms of fogs versus that of directly illuminated fogs.

As a means of discriminating between simulated fuel and oxidizer streams, one immediately thinks of color holography. Much work has been done in this field using continuous wave gas laser sources. The most recent article is that cited in Reference 28. Continuous wave lasers are of too low power for the holography of action events. In a different section of this report, some preliminary work on two-color holography by doubling the radiation of a ruby laser system is discussed. Tests conducted at this laboratory over a year ago were successful, but these were not reported in the open literature. The work is starting again, under sponsorship of the present program.

The University of Wisconsin has described some work on the use of fluorescent photography, or fluorescent measurement using a pulsed ruby laser as the exciting source. This work (Reference 12) was discussed in Section 3.3.4 of this report and would seem to offer some potential with regard to the study of mixture ratio determination using propellant simulants. Ultimately, it may be possible to apply the technique to reacting propellants as indicated previously.

The proposed measurement of liquid rocket engine combustion phenomena under actual firing conditions has been described in a proposal submitted to the Jet Propulsion Laboratory of Pasadena, California (Reference 29). One of the most important pieces of evidence was the holography of a white hot zirconium particle, done as a part of work for the Sandia Corporation. The holography of the zirconium particle was described in the proposal to the Jet Propulsion Laboratory as well as in a talk presented before the Optical Society (References 29 and 21, respectively).

3.5 SUMMARY AND CONCLUSIONS

The various small droplet measuring techniques considered during the Phase I literature review are summarized in Table I. Comments or ratings are given with regard to program objectives, relative cost factors, and significant advantages and disadvantages.

It is apparent that none of the seven droplet measuring techniques will simultaneously meet all of the long-term program objectives cited in the introduction to this section. All of the techniques may be criticized for one or more reasons. In some instances, the functional relationship with drop size is either complicated or based upon assumptions which may be questioned. In other cases, the accuracy of the method cannot be determined, or an undesirable physical disturbance of the spray is produced by the measuring technique.

One point that must be kept constantly in mind in modeling the combustion environment of a rocket thrust chamber is that cold flow studies cannot duplicate the gas velocity environment. Within a few inches of the injector face, gas velocities of several hundred feet per second are typical, with still higher values being reached as the nozzle is approached.

	SMA				
DROPLET DETECTION TECHNIQUES	SPECIFIC PROGRAM LONG TERM OBJECTIVES				
	COMMENTS APPLICABLE TO COLD FLOW PROPELLANT SIMULANTS				
	ESTIMATE OF DROPLET SIZE RESOLUTION (10-500 GOAL)	ABLE TO MEASURE ACROSS 6 INCH DIA. INJECTOR	ABLE TO MEASURE AT ANY AXIAL LOCATION	ABLE TO MAKE MEASUREMENTS AT VERY HIGH DROPLET FLUX LEVELS	ABLE RATIO
ELECTRICAL AND ELECTRONIC SYSTEMS	10-100 μ DROPLET DIA. RANGE DEPENDING UPON THE TECHNIQUE	YES	VERY DIFFICULT	MODERATELY HIGH LEVELS	QUES HAS N DEMO
DEPOSITION AND COLLECTION METHODS	≥ 37 μ DIA. WITH SIEVES < 37 μ DIA. USING MICROSCOPES	YES	NO	MODERATELY HIGH LEVELS	YES TECH
LIGHT SCATTERING TECHNIQUES	RESULTING DEFRACTION PATTERNS YIELD ONLY AN AVERAGE D_{32} VALVE	NO	YES	LIMITED	
FLUORESCENT PHOTOGRAPHY	≥ 10 μ DIA. DROPLETS	UNKNOWN	YES	UNKNOWN BUT QUESTIONABLE	MAY
STREAK PHOTOGRAPHY	QUALITATIVE ESTIMATES ONLY	QUESTIONABLE	YES	LIMITED	
SPARK PHOTOGRAPHY	≈ 10 μ DIA. DROPLETS	YES (DEPENDING UPON DROPLET FLUX INTENSITY)	YES	MODERATELY HIGH LEVELS	
PULSED LASER HOLOGRAP	≈ 10 μ DIA. DROPLETS	YES (DEPENDING UPON DROPLET FLUX INTENSITY)	YES	MODERATE TO HIGH LEVELS	GOO KDP

* TECHNIQUE NOT RATED SINCE THE DATA OBTAINED (FROM THIS TECHNIQUE) IS CONSIDERED INAPPROPRIATE IN RELATION TO THE STATED PROGRAM LONG TERM OBJECTIVES.

A.

Table I. Summary of Small Droplet Measuring Techniques

COMPARISON SUMMARY CHART SMALL DROPLET MEASURING TECHNIQUES						
SPECIFIC PROGRAM LONG TERM OBJECTIVES				ADDITIONAL CONSIDERATIONS		
...BLE TO COLD FLOW PROPELLANT SIMULANTS						
ABLE TO MEASURE AT ANY AXIAL LOCATION	ABLE TO MAKE MEASUREMENTS AT VERY HIGH DROPLET FLUX LEVELS	ABLE TO MAKE MIXTURE RATIO DETERMINATIONS	POTENTIALLY APPLICABLE TO ROCKET ENGINE TEST FIRINGS	RELATIVE COST FACTOR	ADVANTAGES	DISADVANTAGES
VERY DIFFICULT	MODERATELY HIGH LEVELS	QUESTIONABLE HAS NOT BEEN DEMONSTRATED	NO	1.0 - 1.5	1. CERTAIN TECHNIQUES CAN RESOLVE VERY SMALL DROPLET DIAMETERS (APPROACHING 1 MICRON - REFERENCE 2). 2. FOR SOME METHODS, HIGH SAMPLING RATES ARE POSSIBLE (REFERENCE 4).	1. PROBE TECHNIQUES ARE NOT SUITED TO HOT FIRING ENVIRONMENTS. 2. PROBES AND WIRES INTERFERE WITH THE DROPLET SAMPLES. VERY SMALL DROPLETS WOULD BE DISCRIMINATED AGAINST DUE TO INITIAL EFFECTS.
NO	MODERATELY HIGH LEVELS	YES-USING SOME WAX TECHNIQUES	NO	2.0 - 3.0	1. A VERY ACCURATE TECHNIQUE FOR OBTAINING SMALL DROP SIZES. 2. MIXTURE RATIO DETERMINATION IS FEASIBLE. 3. DATA REDUCTION IS SIMPLIFIED FOR LARGER DROP SIZES.	1. TECHNIQUE NOT APPLICABLE TO HOT FIRINGS. 2. COALESCENCE BECOMES A PROBLEM AT HIGHER FLUX LEVELS. 3. FINAL DROP SIZE IS A FUNCTION OF FREEZING PROCESS AND IS NOT NECESSARILY REPRESENTATIVE.
YES	LIMITED	NO	QUESTIONABLE RESULTS	NOT RATED *		1. THE METHOD YIELDS ONLY A D_{32} VALUE FOR THE DROPLET SPRAY. 2. THE TECHNIQUE IS SENSITIVE TO CHANGE IN REFRACTIVE INDEX OF THE SURROUNDING MEDIUM. 3. EXTENSION OF THIS METHOD TO A RAPIDLY VAPORIZING DROPLET IS QUESTIONABLE.
YES	UNKNOWN BUT QUESTIONABLE	MAY BE POSSIBLE	YES USING LASER ILLUMINATED PHOTOGRAPHY TECHNIQUES	3.0 - 3.5	1. METHOD MAY BE APPLIED TO THE HOT FIRING SITUATION. 2. MIXTURE RATIO DIFFERENTIATION WITH SIMULATED PROPELLANTS APPEARS FEASIBLE. 3. TEN MICRON DROPLETS HAVE BEEN RESOLVED.	1. LASER ENERGY HAS A DISTORTING EFFECT ON THE DROPLET GEOMETRY. 2. DEPTH OF FIELD LIMITATIONS ARE INHERENT.
YES	LIMITED	NO	YES	NOT RATED *	1. APPLICABLE TO HOT FIRING SITUATION.	1. DIFFICULT TO ANALYZE DROPLET SIZE. 2. DEPTH OF FIELD PROBLEMS COMPLICATE THE STREAK RECORD FOR ANALYSIS. 3. RESULTING DATA IS SOMEWHAT QUALITATIVE WITH REGARD TO PROGRAM OBJECTIVES.
YES	MODERATELY HIGH LEVELS	NO	YES	1.0 (REFERENCE)	1. APPLICABLE TO HOT FIRING SITUATION. 2. DROPLET DIAMETERS APPROACHING 10 MICRONS HAVE BEEN RESOLVED. 3. SPARK TECHNIQUE HAS BEEN REFINED AND DEVELOPED TO AN ADVANCED STATE.	1. SPARK INTENSITIES NECESSITATE FAST FILM AND ACTIVE DEVELOPERS WHICH TEND TO DEGRADE THE IMAGE. 2. DEPTH OF FIELD LIMITATIONS ARE INHERENT.
YES	MODERATE TO HIGH LEVELS	GOOD POTENTIAL-USING KDP CRYSTAL	EXCELLENT POTENTIAL	0.5 - 1.5	1. ULTIMATE RESOLUTIONS IN THE ORDER OF 10 MICRONS IS POSSIBLE. 2. DEPTH OF FIELD IS NOT A LIMITATION. 3. ULTIMATE APPLICATION TO HOT FIRING SITUATION APPEARS QUITE REALISTIC.	1. THE TECHNIQUE REQUIRES ADDITIONAL DEVELOPMENT AND DEFINITION WITH REGARD TO THE PROGRAM OBJECTIVES.

B.

For this reason, and the fact that in all but the largest engines the majority of the combustion occurs in these same first few inches, the droplet history of all but the largest droplets takes place in this vital region near the injector. To place probes or windows to observe cold flow events at distances of a foot or more downstream is unrealistic from the standpoint of modeling the true droplet events occurring within a liquid rocket combustor.

Of the several evaluating criteria, the potential application of a given technique to the hot firing situation is considered one of the most important factors. Droplet studies and theories developed around cold flow models must ultimately be verified by examining the combustion process in a rocket engine. Those techniques which are not applicable to hot firings are, therefore, less desirable.

From the literature survey results, there appear to be two techniques which show promise of meeting (or at least approaching) the program long-term objectives. These techniques are direct photography (using either a spark source or laser illumination) and holography. Direct photography has been used for many years. Its usefulness or versatility is largely restricted by the intensity of the light sources available. Potential improvements in spark intensity and the advent of the laser give promise of extending the limits of this technique.

The application of holography to the study of small droplets is entirely feasible. Holographic techniques can provide resolution to 10 microns or less. It is also feasible to apply this technique to the study of combustion phenomenon as well as cold flow determinations. One of the most valuable features of holography is the fact that one may capture events taking place in a scene-volume rather than a two-dimensional plane, as with conventional photography. The holographic record may subsequently be reconstructed and examined with any desired optical instrument or simply with the human eye. In the case of droplet spray patterns, the drop formations and size distributions may be examined at any plane within the recorded scene. In effect, a three-dimensional model may be constructed of the droplet distributions within a given flow pattern. Further, this data may be obtained from one test rather than a series of repetitive tests.

4. EXPERIMENTAL STUDIES

4.1 PHASE I OBJECTIVES

During Phase I, experimental work was conducted in the areas of droplet detection and data reduction to support and augment the literature survey activities. The objectives established for the Phase I experimental studies were as follows:

a) Make approximately 10 holograms of a like-on-like impinging stream element

b) Attempt a two-color differentiating holography technique that will detect mixture ratio distributions within a droplet spray pattern

c) Conduct spark photographic studies of the single element injector used in the holography tests

d) Demonstrate feasibility of the computer-based densitometer data reduction technique

A discussion of the work accomplished in each of these areas is presented in succeeding paragraphs.

4.2 HOLOGRAPHIC STUDIES

Thirty-six-holograms were made during the Phase I effort. The equipment used, experimental procedures and test results of this work are presented in the following sections.

4.2.1 Water Flow Apparatus and Operation

Two injector elements were used in the cold flow holography experimentation. The elements tested were furnished by Princeton University. The photograph of Figure 4-1 and drawing of Figure 4-2 illustrate Princeton injector element serial number JP4M-232A. The companion Princeton injector, serial number JP4M-242A, is of similar configuration. Both injector elements consisted of two side-by-side impinging stream flow circuits. The internal geometry of these like-on-like injector flow passages is shown in the cross-sectional detail "A-A" of Figure 4-2. This cross section is typical for both flow circuits within the injector element body. The side-by-side flow passages may be flowed separately or simultaneously as desired. The nominal

Figure 4-1

Close-up view of Princeton University like-on-like injector elements. Impingement is at a 90-degree included angle with a zero impingement distance. Stream impingement takes place within counterbored holes in the injector face.

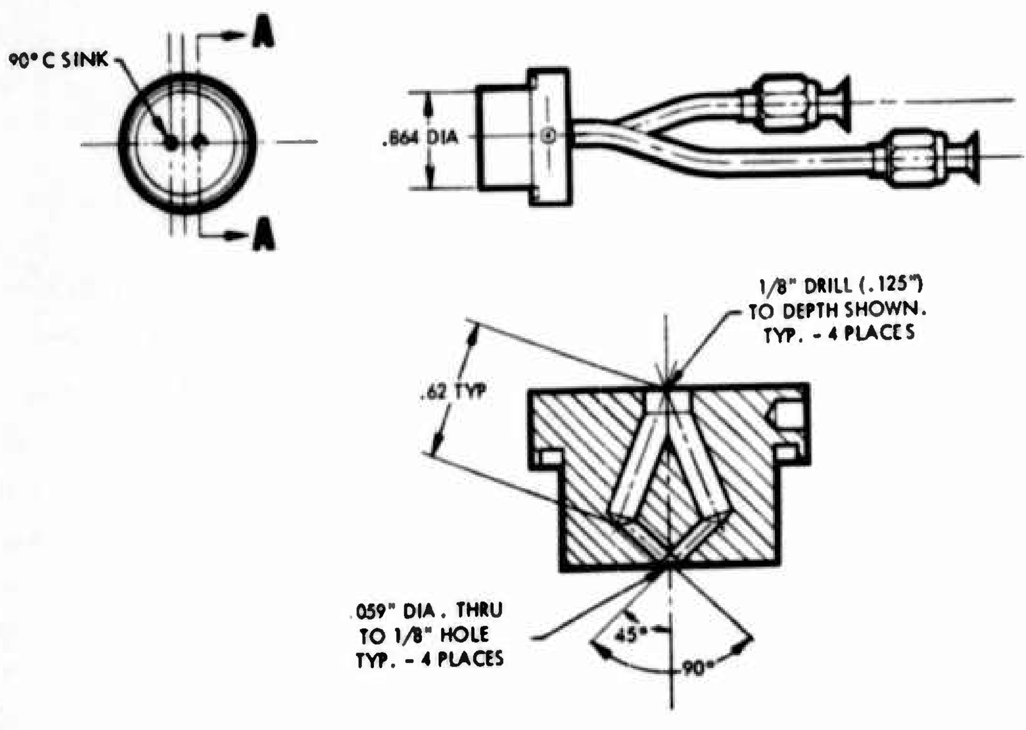


Figure 4-2. Schematic of like-on-like impinging stream injector element used for preliminary holography studies.

design and operating characteristics of the elements are as follows:

Orifice diameters	0.059 inch
Impingement angle	90 degrees
Water flow rate	0.165 lb/sec
Pressure drop	100 psi

The curve in Figure 4-3 shows the relationship of water flow rate versus pressure drop for both Princeton injector elements.

Initial holography studies were made by flowing water through only one of the two impinging like-on-like flow circuits of injector serial number JP4M-242A. Subsequently, injector serial number JP4M-232A was also studied. Holograms of single and dual flow conditions were made.

The injectors were installed in the water flow system shown in Figures 4-4 and 4-5. This system consists of a water supply tank, burst disc assembly, 10 micron filter, manual and solenoid-operated shutoff valves and the test spray element. Arrangement of these components is shown in the schematic diagram of Figure 4-6.

A regulated GN_2 supply in the laboratory was used to pressurize the distilled water feed system. The tank shown has a 1000 cubic inch volume and a maximum working pressure of 400 psi. Prior to installation in the test rig, the tank was subjected to a proof pressure test at the allowable working pressure of 400 psi to confirm structural integrity. A burst disc assembly rated at 195 psi was installed between the tank and the GN_2 supply to prevent tank overpressure in the event a gas regulator should fail.

4.2.2 Laser Illuminator Description

The ruby laser illuminator is conventional and consists of an oscillator followed by two power amplifier stages. The system emits a single pulse of light of 0.64 micron wavelength of approximately 0.1 microsecond duration and of approximately 3 joules content. The ruby laser oscillator is described in a paper published in the scientific literature (Reference 30). It contains the following key components: namely, a 1/2-inch diameter by 3-3/4-inch long Czochralski grown 60° oriented ruby laser rod of high homogeneity, an internal aperture, an air space Glan polarizing prism,

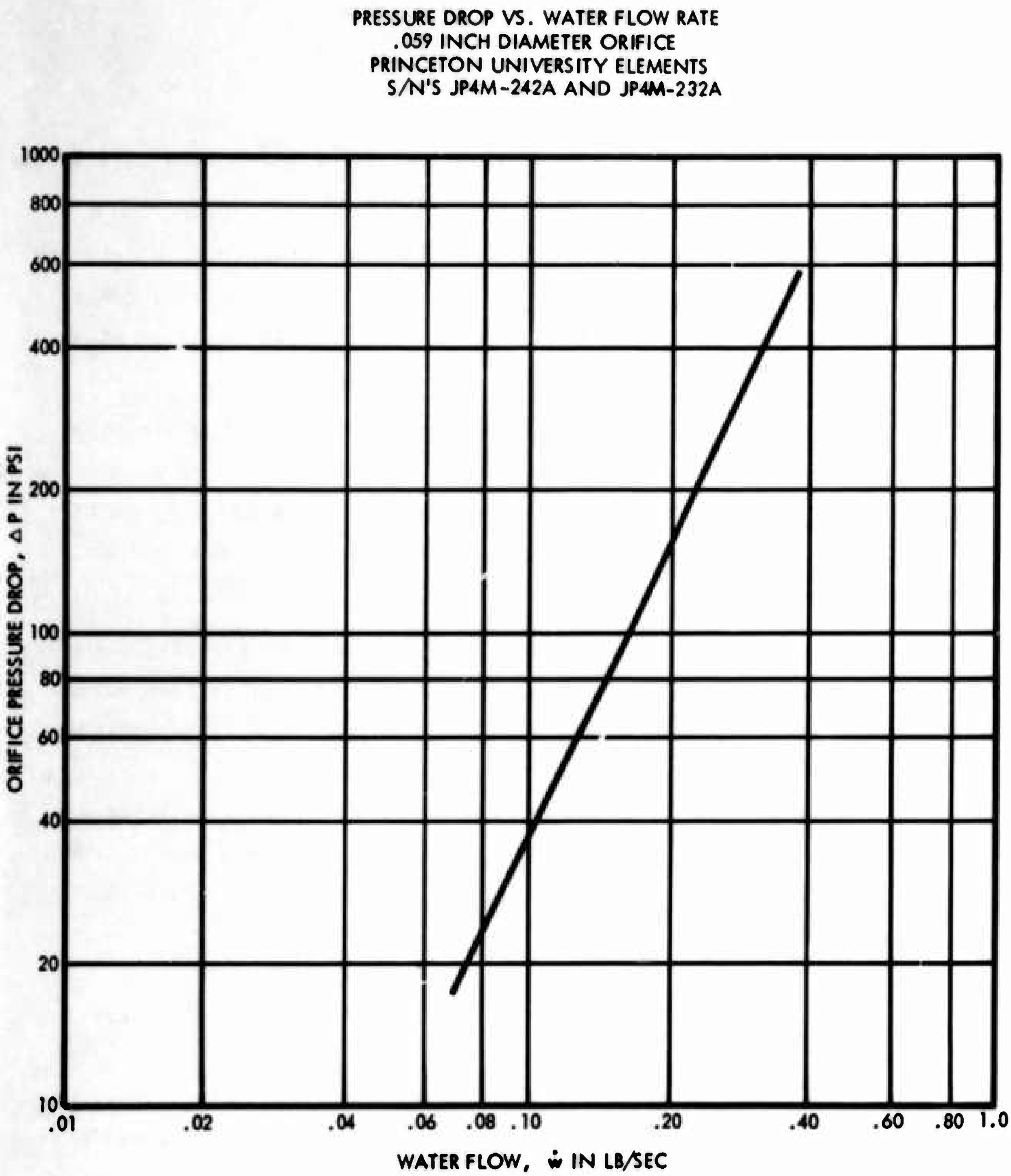


Figure 4-3. Water flow rate versus pressure drop for Princeton University injector test elements.

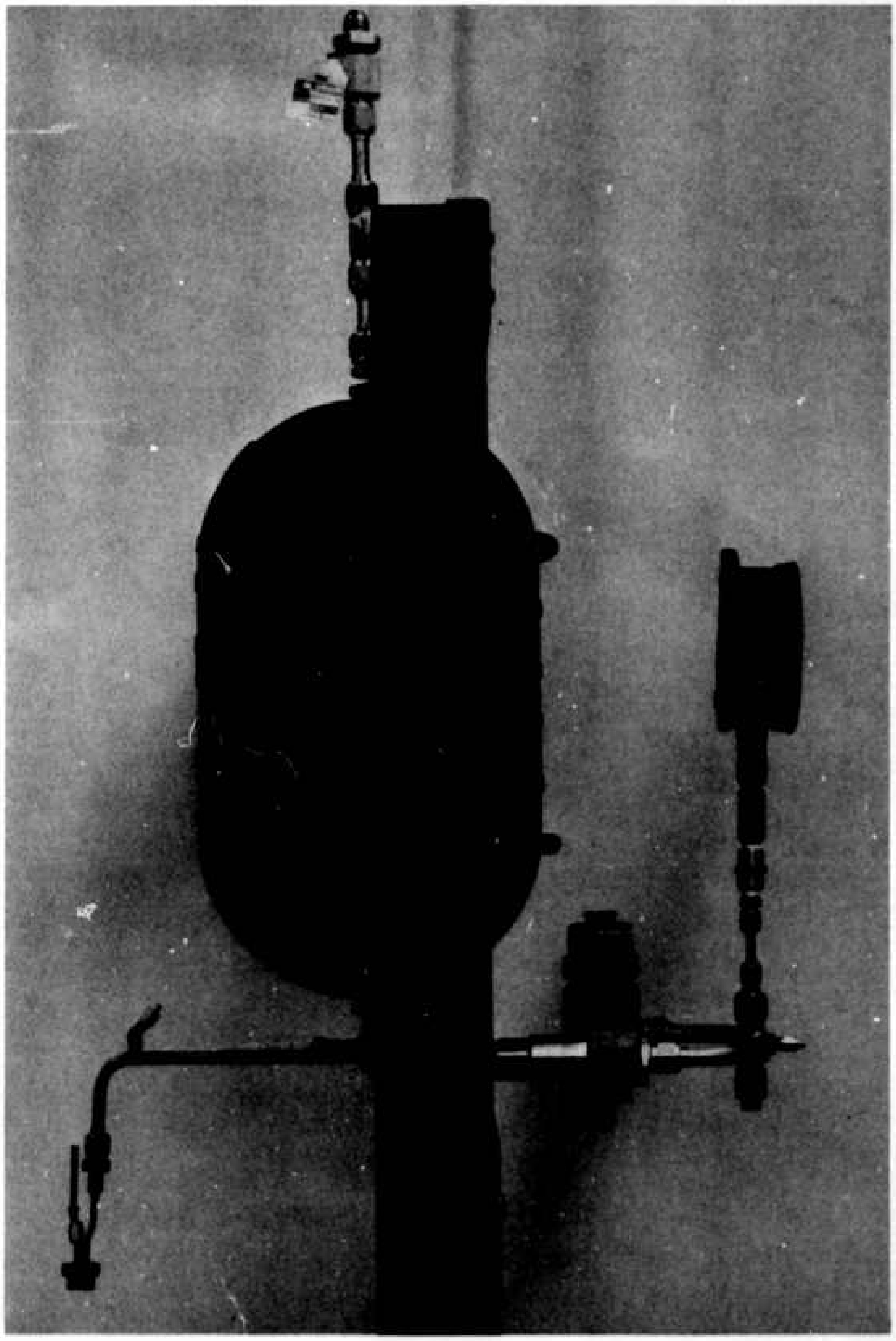


Figure 4-4. Side elevation of water flow feed system mounted on a portable rack. Test injector element is shown in lower left-hand portion of photograph.

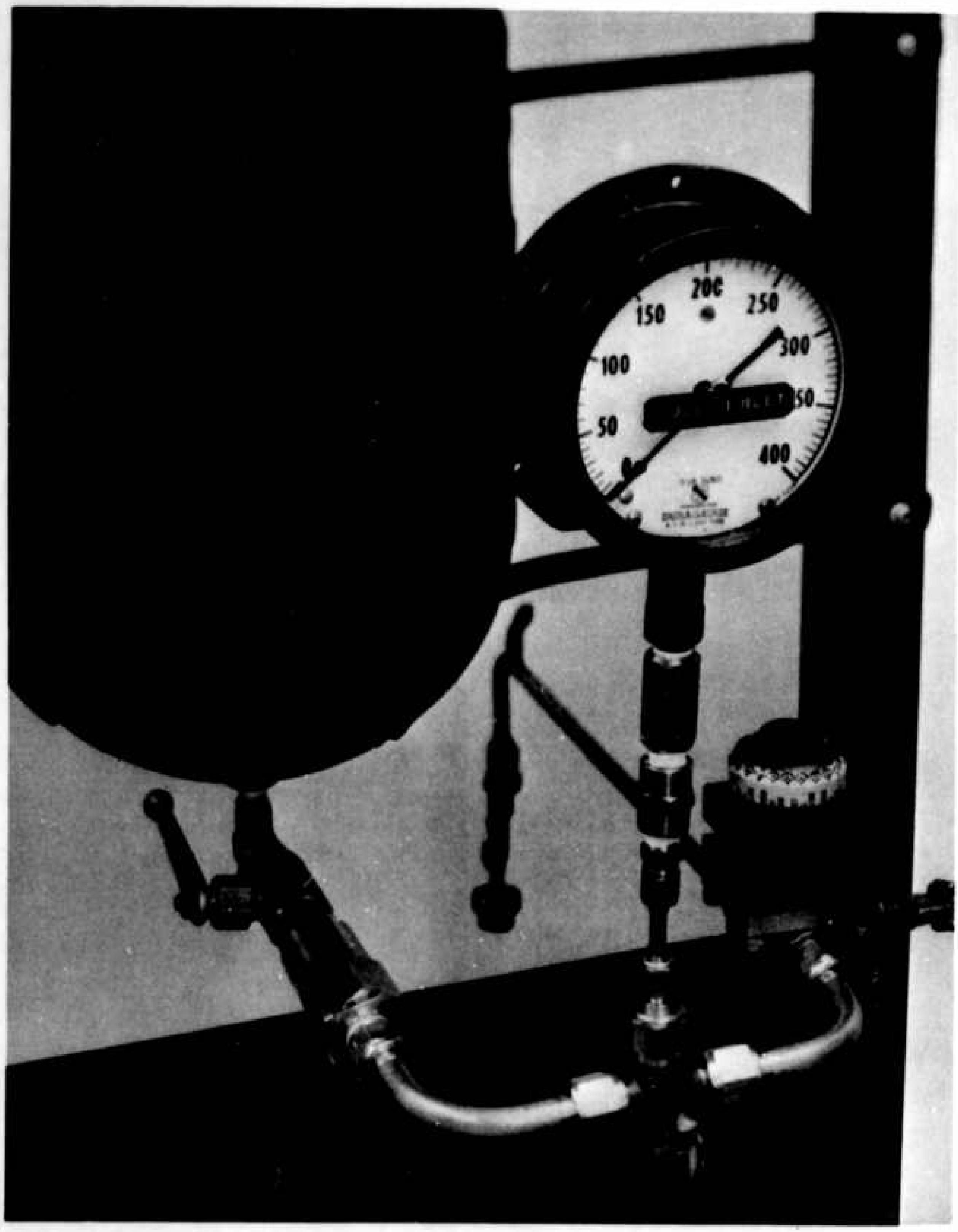


Figure 4-5. Close-up view of water flow system showing tank, pressure gage and solenoid-operated shutoff valve. Test injector element may be seen in background.

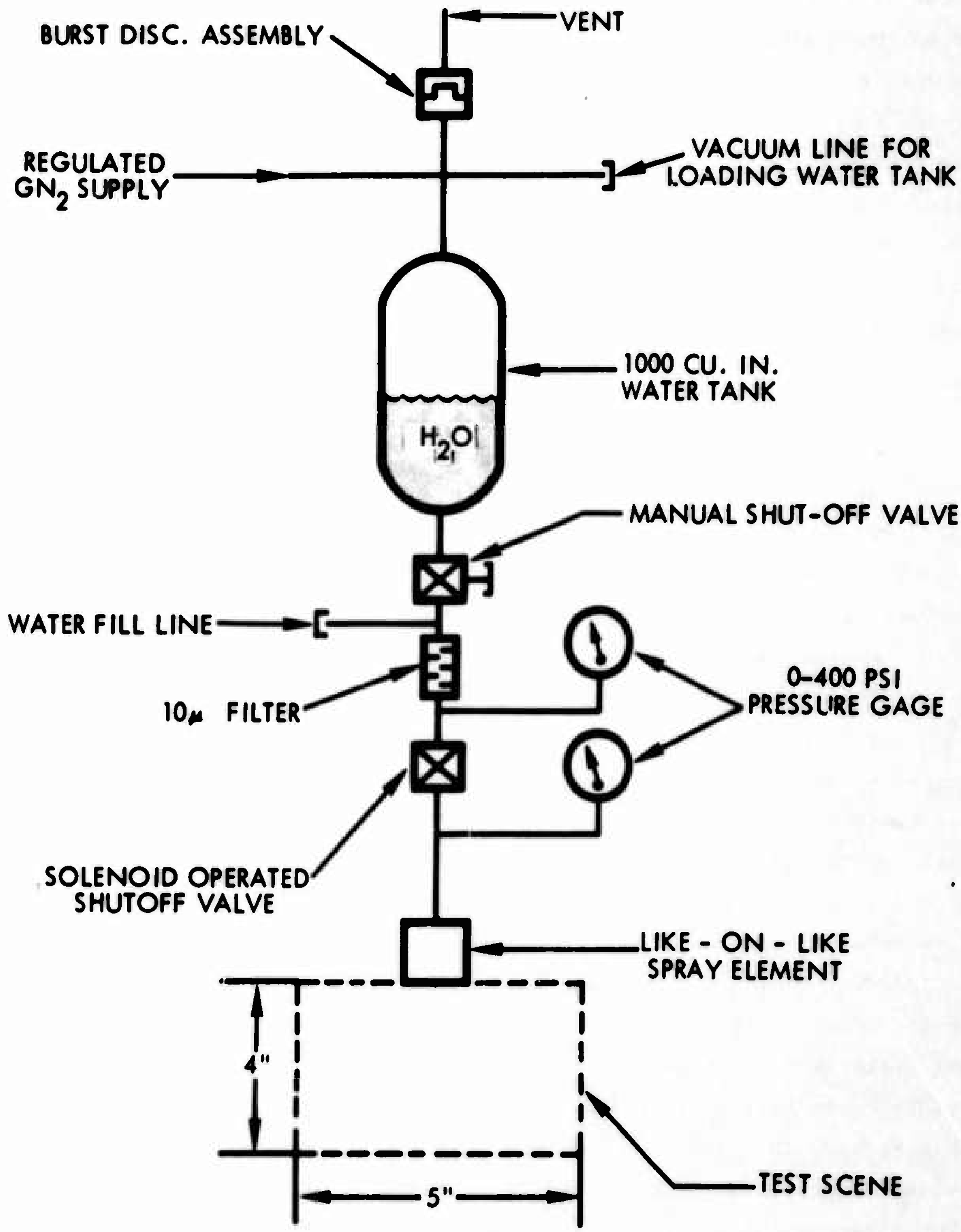


Figure 4-6. Schematic of water flow system.

a nitrobenzene Kerr cell, a 99 percent reflecting dielectric coated flat, and a highly parallel 1/8-inch thick sapphire flat. The latter item is known as a resonant reflector, which, with the dielectric coated flat, comprise the optical resonator of the laser oscillator. The other cited components are mounted between these two elements. The beam from the oscillator passes through the resonant reflectors and is expanded by a Gallien telescope so as to completely fill the cross section of the 1/2 x 3-3/4 inch laser rods in each individual amplifier housing. The amplified beam is then further expanded by a second telescope and directed into the "holocamera". This latter device acts to compensate the limited spacial and temporal coherence of the radiation ruby laser illuminator (Reference 31).

4.2.3 Holocamera

The holocamera which is in existence at TRW Systems is special in the sense that it was designed to produce pulsed laser holograms with an extremely wide range of viewing angles. It is referred to as a "focused ground glass holocamera" to distinguish it from others of simpler and less sophisticated design. A schematic of the device is shown in Figure 4-7. The beam from the laser illuminator is incident upon an optical wedge beam splitter which divides the beam into three beams: namely, a reference beam reflected from the first surface of the wedge, a photocell beam from the second surface of the wedge, and a scene beam, transmitted directly through the wedge. The reference beam, after being reflected from two front surface mirrors, was directed into a beam inverter. The beam inverter consisted of a prism cluster from a pair of binoculars. The beam was then diverged by a simple double concave lens of approximately -22 cm focal length. The focal length was chosen so that the diverged beam just filled the skew mounted standard 4x5 inch glass photographic plate. The beam reflected from the back surface of the wedge was incident on a mirror and directed onto a piece of frosted glass placed before a biplanar photodiode. A variable aperture was placed before the photocathode to adjust the amount of light directed upon the photocathode and the magnitude of the photoelectric pulse. The current pulse from the photodiode was displayed by a traveling wave oscilloscope having a resolution of 0.3 nanosecond.

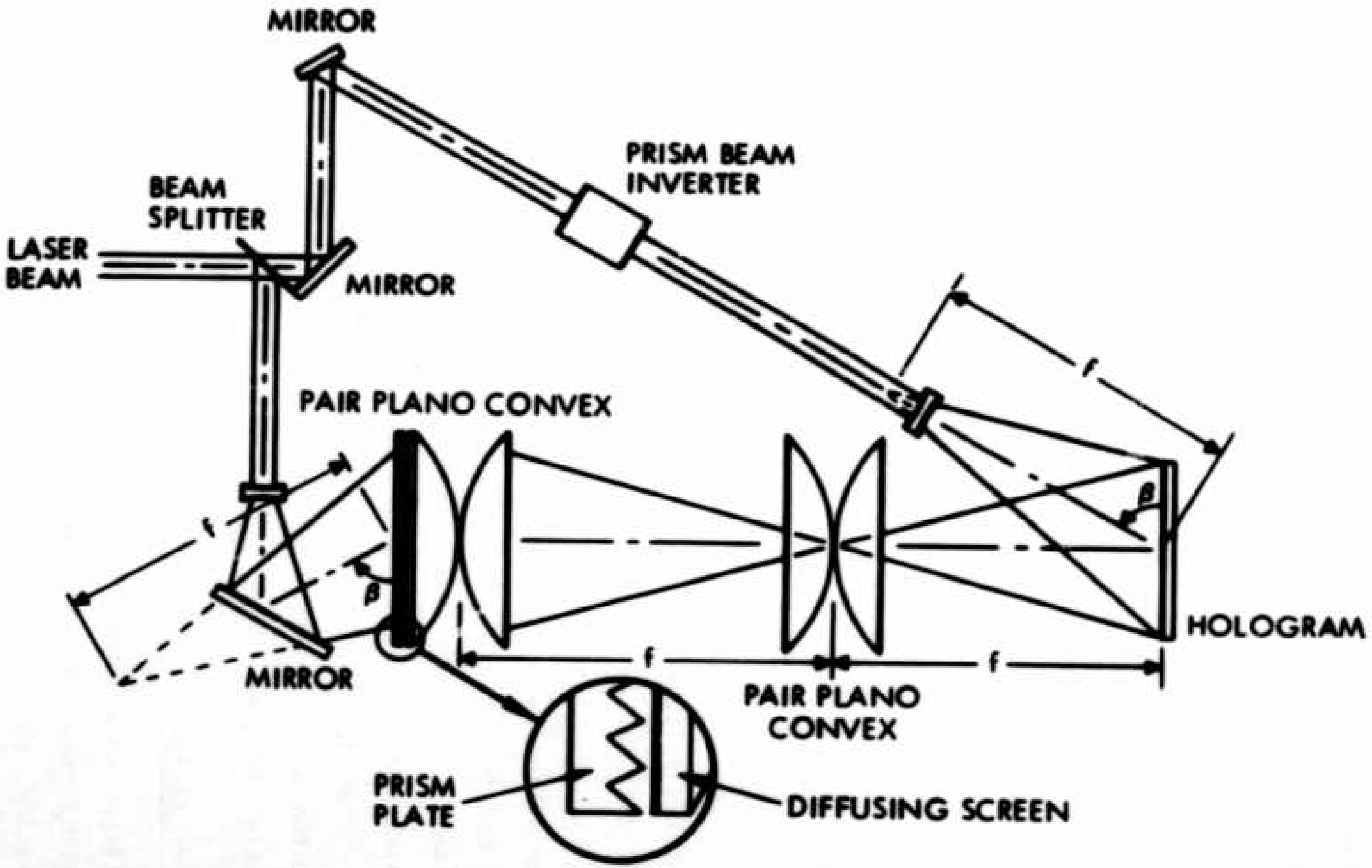


Figure 4-7. Schematic of the "focused ground glass holocamera" used to provide spacial and temporal matching of a laser beam. A holocamera of this type was used to make the transmission holograms of the simulated fuel and oxidizer interaction shown in this report.

The "scene beam" or beam which passes directly through the wedge beam splitter was diverged by a second negative lens of the same focal length as the lens in the reference beam path. The diverged radiation was reflected off a mirror and spread across a ground glass diffuser. The angle of incidence onto the diffuser was the same as that of the reference beam across the hologram plate.

The ground glass screen was followed by a second plate which was fabricated with a prismatic cross-section. This plate served to refract the diffuse scene beam down the axis of the large lens system. The focusing system consisted of two pairs of large standard condensing lenses. The intermediate pair acted to focus the light scattered by the ground glass onto the 4x5 inch glass photographic plate. A second pair of lenses, in close proximity to the prismatic plate, acts as a pair of field lenses serving to direct a larger fraction of the scattered light into the pair of focusing lenses. They also serve to compensate for the increasing optical path length at increasing distances from the axis of the focusing system.

If one traces a ray from the laser, one will find that, after being divided by the wedge beam splitter, the two rays combine with themselves in the photographic plate and that both of the rays have traveled over the same optical path length. The accuracy of the alignment of the focus of the lenses, the superposition of the scene and reference beams at the recording plate, and the match of the optical path lengths are all determined by spacial and temporal coherence of the ruby laser illuminator. In general, it has been found that for maximum quality holograms the beams should be superimposed to within 10 percent of their cross-sectional area, and the path lengths should be matched to within a centimeter. Photographs of the holocamera apparatus are shown in Figures 4-8 and 4-9.

4.2.4 Test Procedure

The injector test elements were connected to the water flow stand and positioned within the holocamera scene volume. Initially, only one side or flow passage of the Princeton University injector element was utilized since the feasibility of basic droplet detection was the only objective of these tests. As such, the spray pattern produced was adequate for equipment checkout and early demonstrations. Subsequently, holograms were made with both sides of the element flowing.

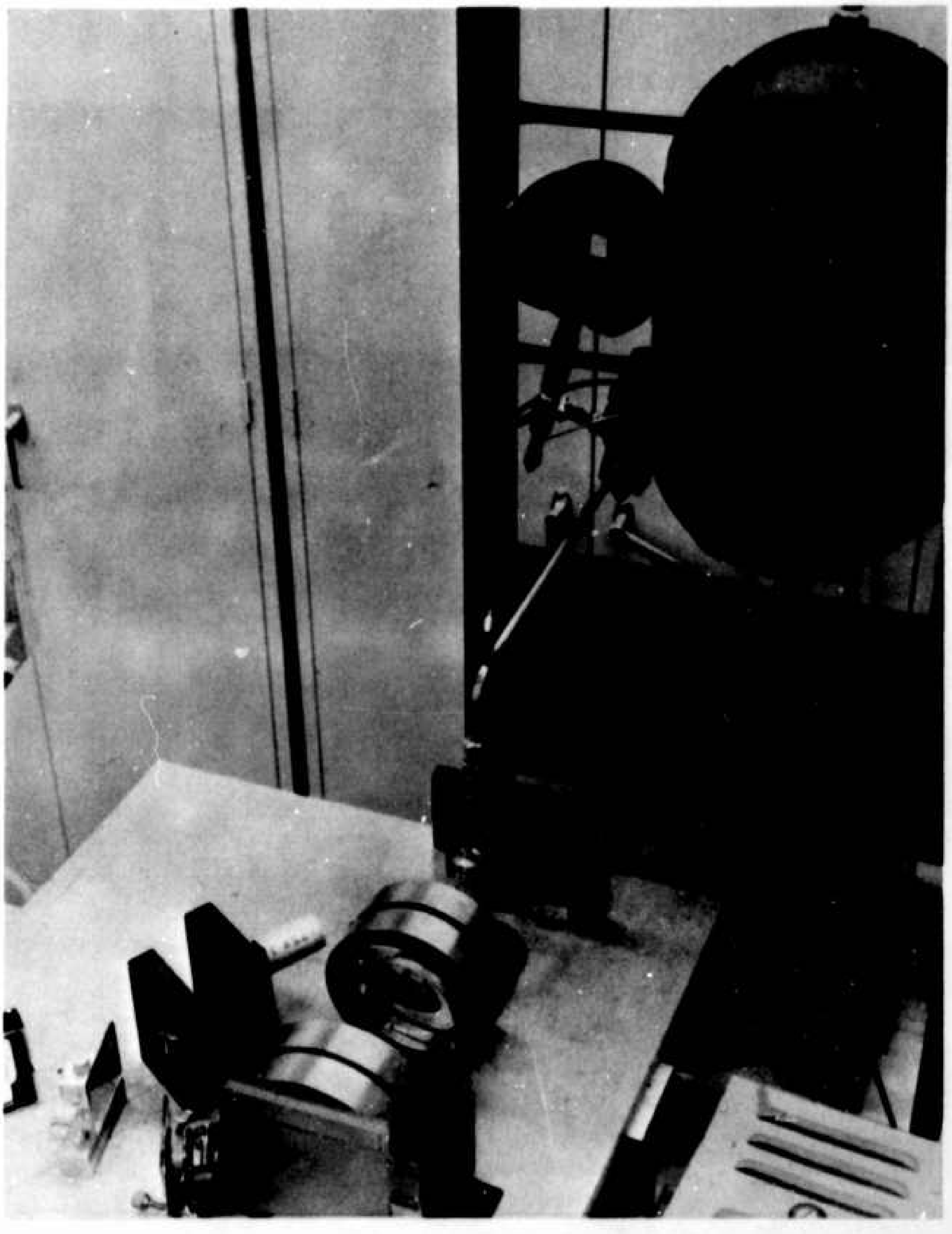


Figure 4-8. Photograph of the arrangement used to holograph water spray patterns. The water flow system is in the background. Some of the components of the holocamera are seen in the foreground. The injector is within the scene volume of the holocamera just before the plate holder.

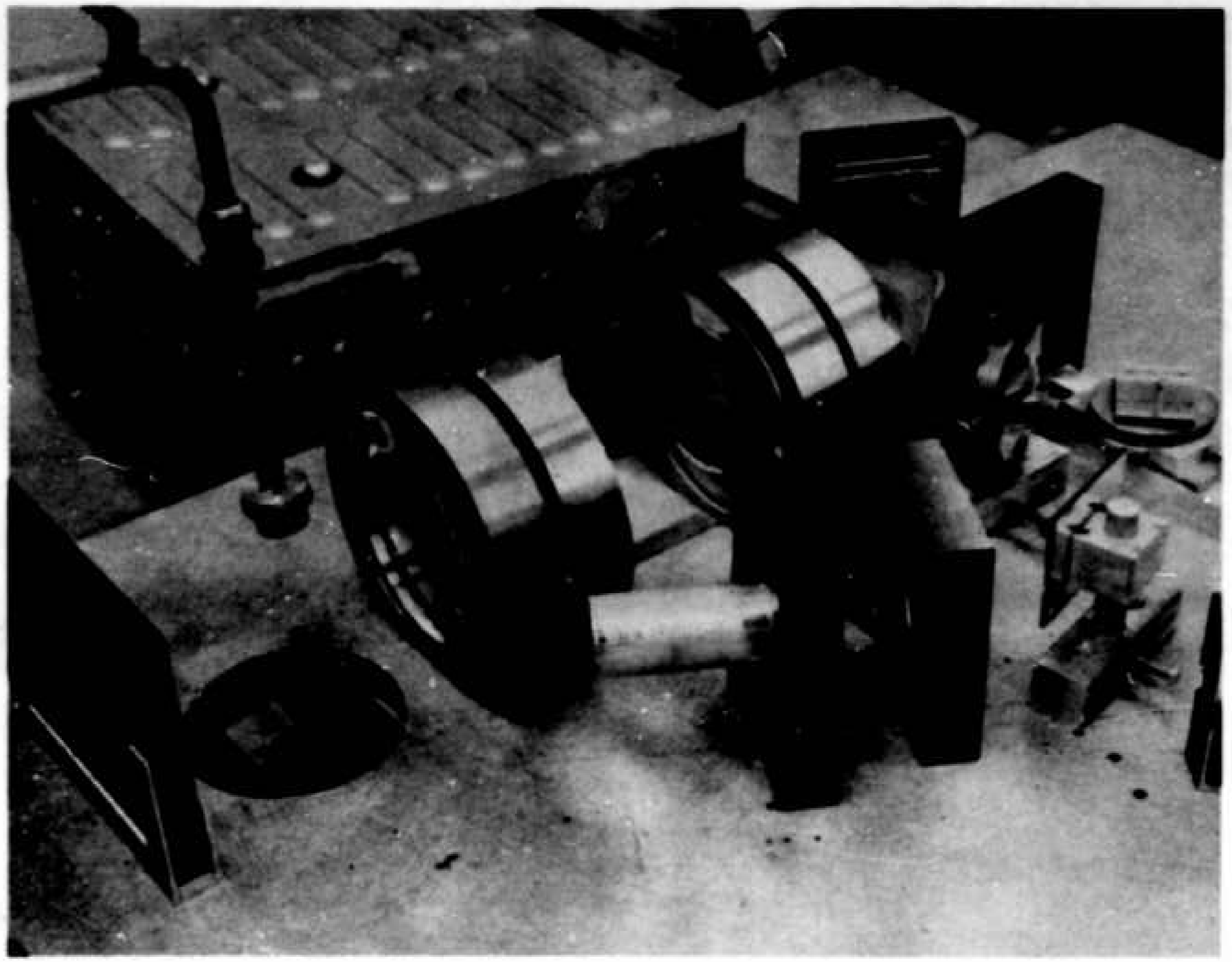


Figure 4-9. Photograph of the "focused-ground-glass" holocamera used to record the simulated spray patterns from a liquid rocket engine injector. A Princeton injector element can be seen mounted within the scene volume of the holocamera. The divergent reference beam is in the foreground, incident obliquely on the 4x5 inch 649F photographic plate in the Graflex holder. The power supply in the background actuated the water flow solenoid shutoff valve.

To expose the film plate, the coil on the solenoid shutoff valve of the water flow system was connected to the input of a Tektronix 545 oscilloscope. The 150-volt saw-tooth output from the oscilloscope was connected to the input of a second Tektronix Type 555 oscilloscope. The first oscilloscope was set to sweep in one-half second. By adjusting the sensitivity of the trigger of the second oscilloscope, one could control when the laser was fired relative to the opening of the valve on the water flow system. The second oscilloscope was used to control the firing of the Kerr cell ruby laser illuminator.

Holograms were made of spray patterns of the Princeton elements at pressures of 50, 75, 100, 150 lbs/in^2 across the injection orifices. This resulted in the following flow conditions:

ΔP_{inj} (psi)	$\dot{w}_{H_2O}$ (lb/sec)	V_{stream} (ft/sec)
50	0.115	86.2
75	0.141	105.5
100	0.162	121.9
150	0.200	149.3

The holograms were recorded on Eastman 649F plates, developed in HRP developer (development time was typically 8 minutes), rinsed in water, and fixed. After the holograms had been developed and dried (in air overnight), they were available for study and recording. Photographs of the hologram reconstructions are presented and discussed in the succeeding text.

4.2.5 Reconstruction Apparatus and Procedure

The reconstructing arrangement is shown in Figure 4-10. Holograms were mounted in a frame holder before the output of a Model 124 Spectra Physics helium neon-laser. A bellows copy camera with a 150 mm focal length Schneider lens (No. 5823045) was used to photograph the reconstructions of the various droplet spray holograms.

Pictures were recorded on Polaroid Type 55 P/N film, typically 5 seconds with the lens at f/5. In most instances, an image of one-to-one magnification image was projected on the film. Photographs of the various recorded holograms were taken at different camera positions relative to the best focus of

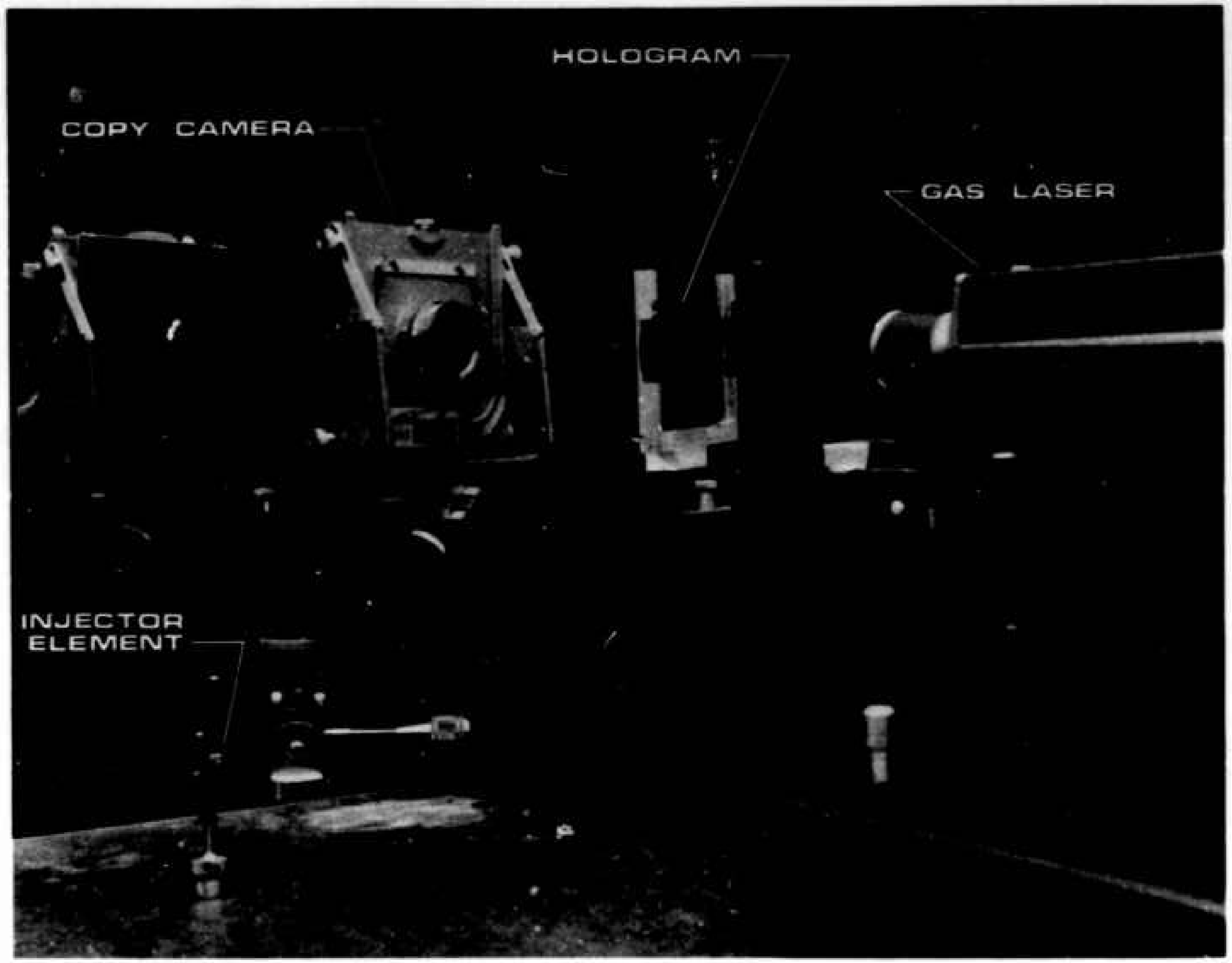


Figure 4-10. Equipment used to photograph the reconstruction of the pulsed ruby laser holograms of the simulated liquid rocket injector element spray patterns.

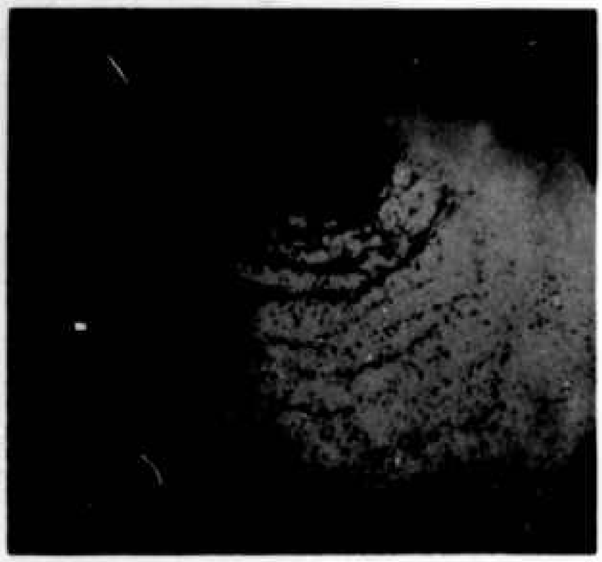
the water spray pattern. The camera was moved appropriately to keep the magnification of the in-focus image the same. Pictures were taken at different focal positions as well as different settings of the aperture on the camera lens.

4.2.6 Discussion of Holographic Test Results

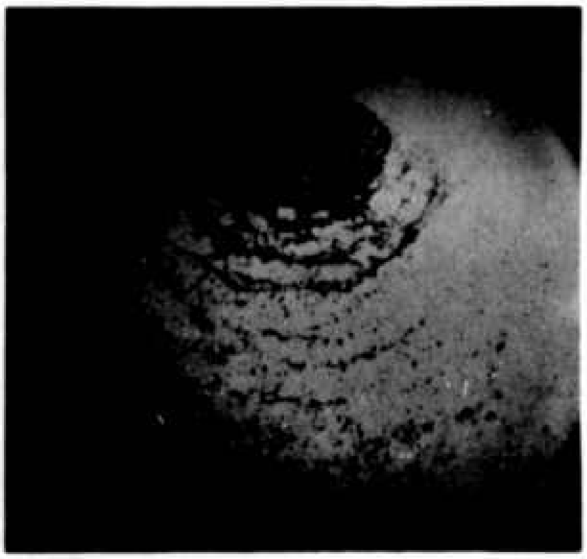
The first set of holograms made during Phase I used Princeton injector element JP4M-242A. As indicated earlier, only one flow passage of the injector was utilized resulting in a single droplet spray fan. Typical examples of reconstruction photographs made from these initial holograms are shown in Figures 4-11 through 4-13. Figure 4-11 illustrates the droplet spray pattern obtained with a pressure drop of 50 psi across the impinging stream orifices. Three of the four photographs in this figure were taken with the lens at f/5 and one with the lens at f/16. The greater depth of field obtained with the lens set at f/16 is apparent in that the granularity phenomena of the coherent light in the photograph background is more discernible. With the lens set at f/5 (the remaining three photographs) the granularity of the background is less noticeable.

In addition to the two different lens settings, the photographs differ by the location of the fixed focus copy camera relative to the central plane of the spray fan. A plane passing through the axial centerline of the injector body and resulting spray fan was arbitrarily designated as the "zero" centimeter reference. A plus one centimeter, then, indicates that the focal plane is one centimeter beyond the "zero" reference plane relative to the observer. Conversely, a negative one centimeter indicates the focal plane is one centimeter away from the reference plane on the near side -- relative to the observer.

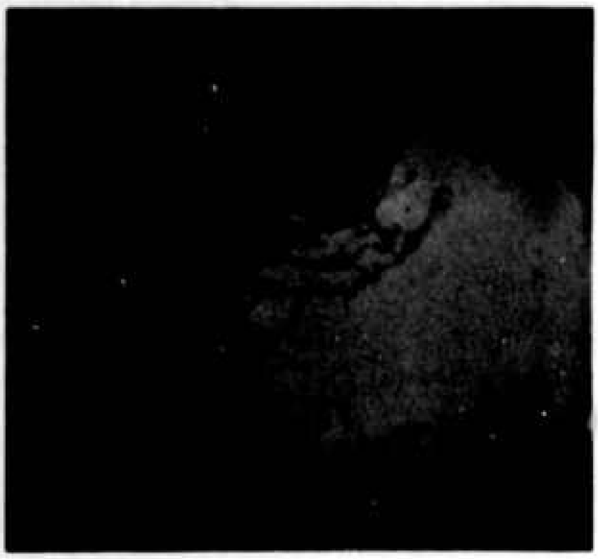
Figures 4-12 and 4-13 illustrate the same sequence of photographs as described for Figure 4-11, except that the injector pressure drop was established at 100 and 150 psi, respectively. Examination of these three series of reconstruction photographs reveals a rather typical droplet formation sequence of events. The resultant flow emanating from the impinging streams forms a coherent fan-shaped mass. This is followed by breakup of the fan into ligaments and eventual further breakup and droplet formation.



f/16, 0 cm



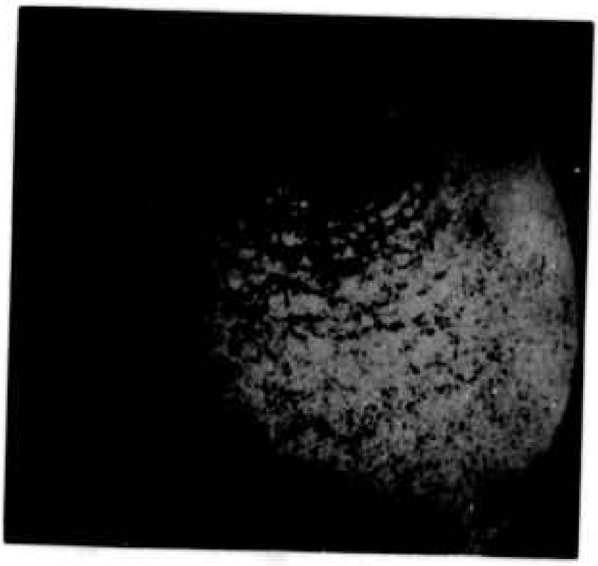
f/5, 0 cm



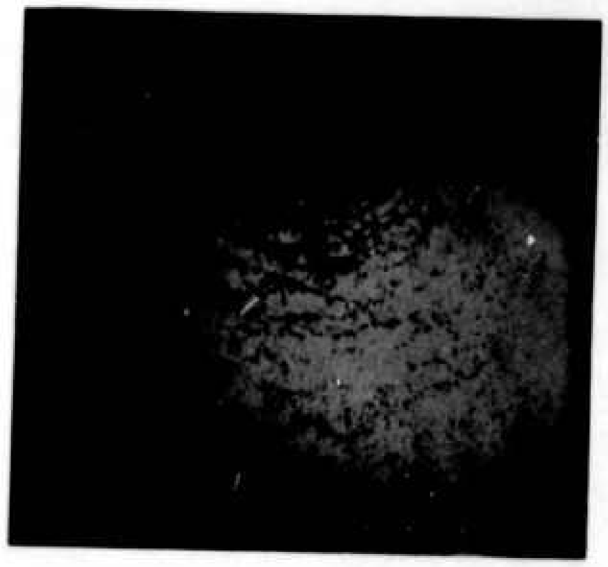
f/5, -1 cm

f/5, +1 cm

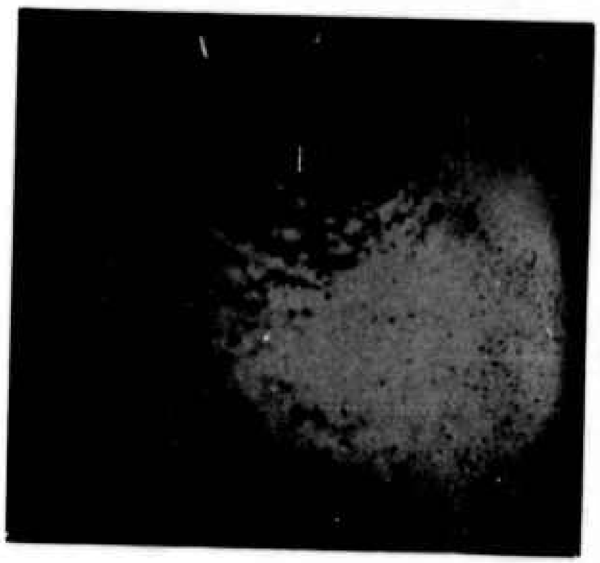
Figure 4-11. Four photographs of the reconstruction of the ruby laser hologram of Princeton injector JP4M-242A operating with water at a pressure drop of 50 lb/in^2. The pictures differ by the lens aperture setting and the position of the copy camera relative to the best focus of the fan.



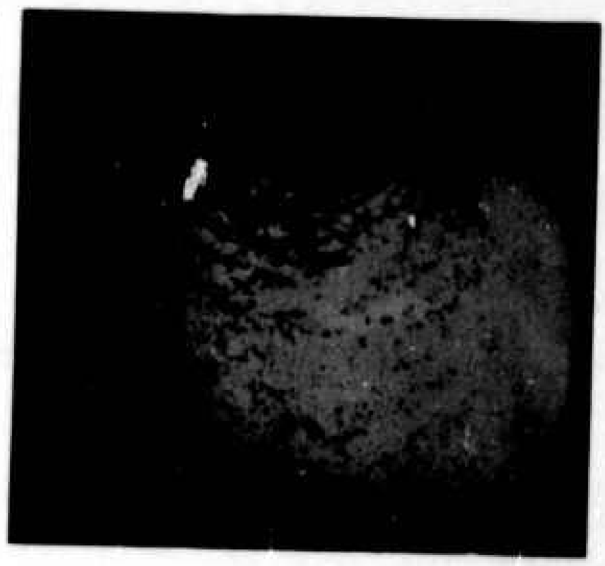
f/16, 0 cm



f/5, 0 cm



f/5, -1 cm



f/5, +1 cm

Figure 4-12. Four photographs of the reconstruction of the ruby laser hologram of Princeton injector JP4M-242A operating with water at a pressure drop of 100 lb/in^2. The pictures differ by the lens aperture setting and the position of the copy camera relative to the best focus of the fan.

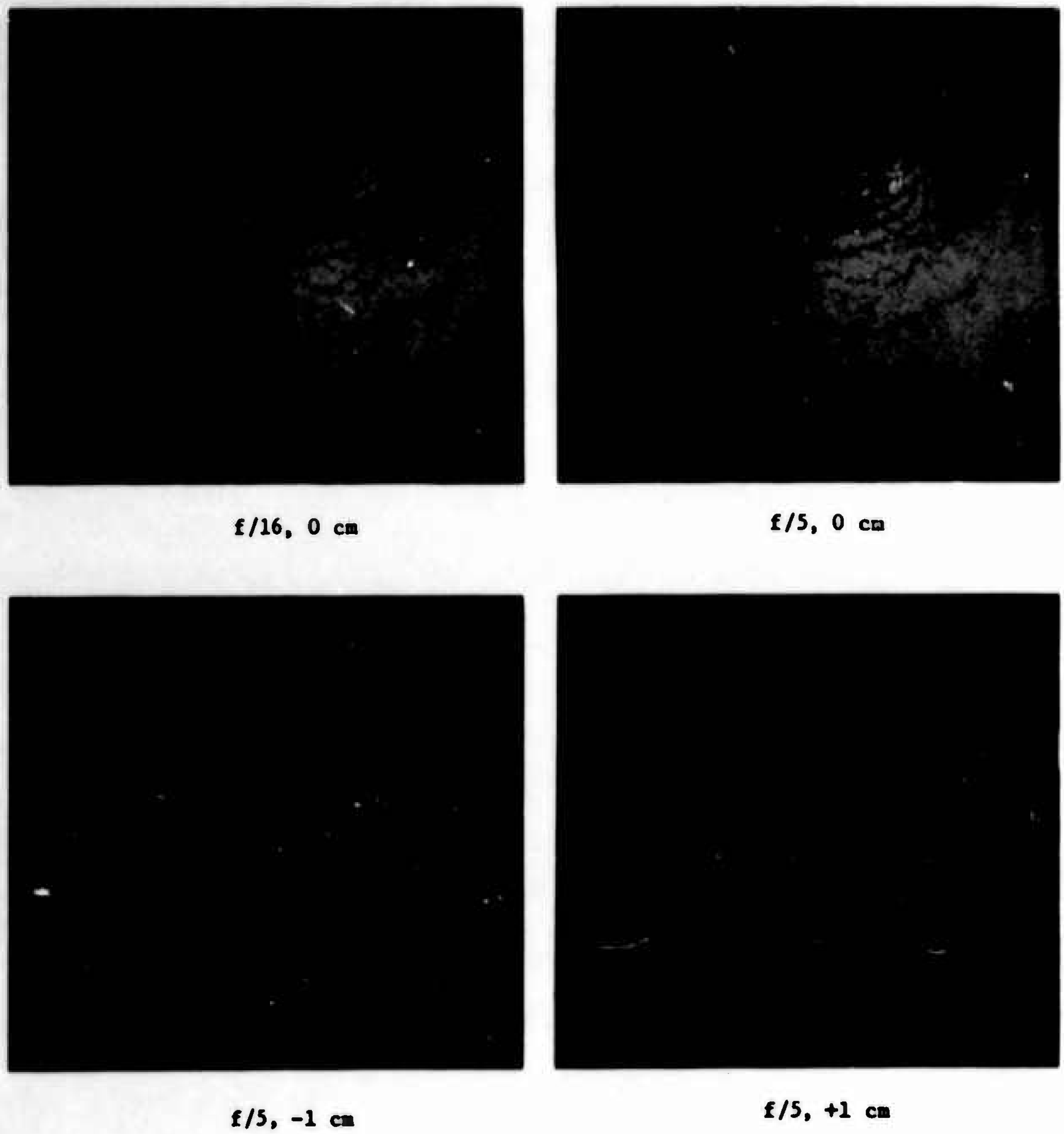


Figure 4-13. Four photographs of the reconstruction of the ruby laser hologram of Princeton injector JP4M-242A operating with water at a pressure drop of 150 lb/in^2. The pictures differ by the lens aperture setting and the position of the copy camera relative to the best focus of the fan.

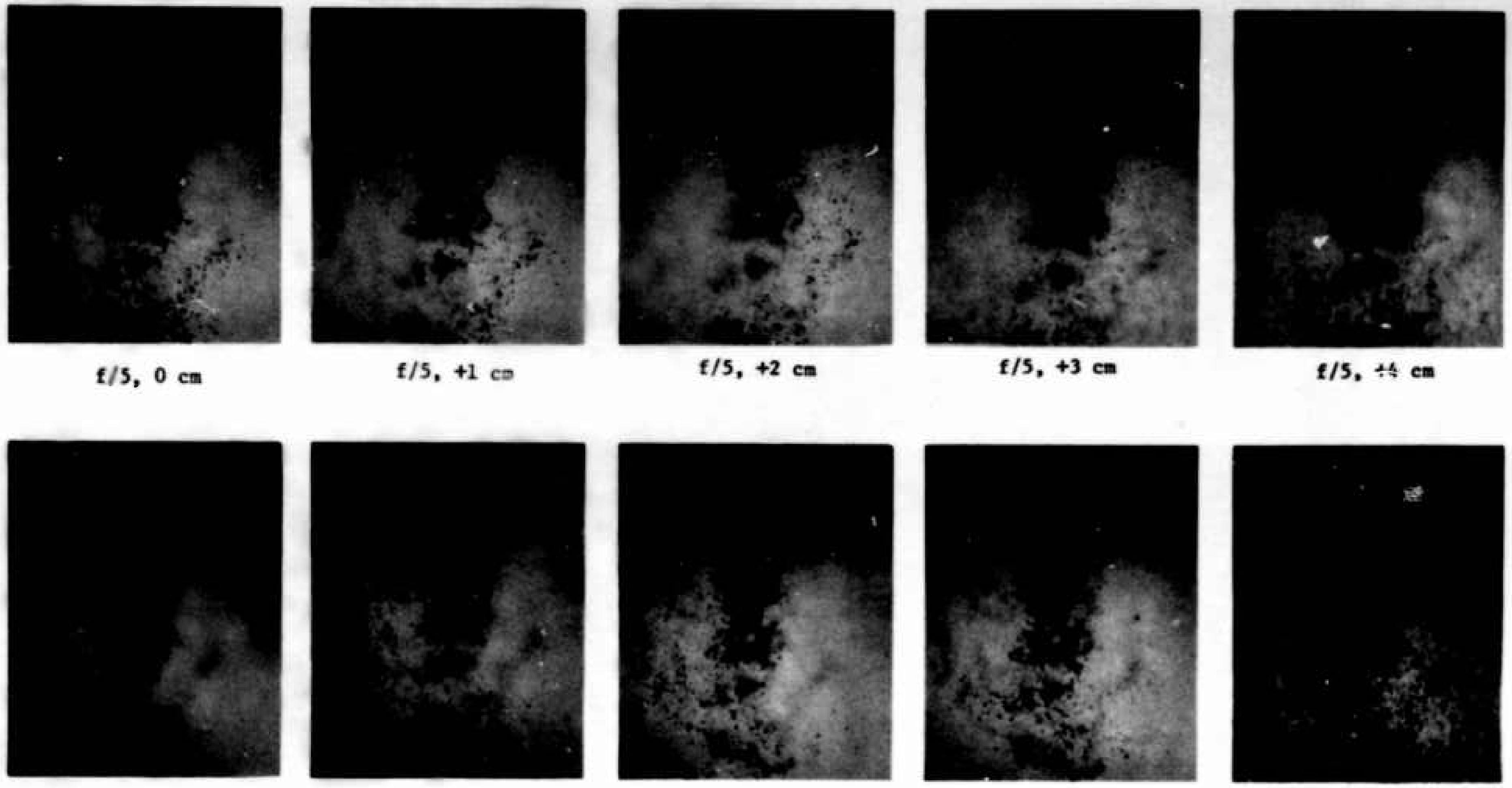
Again reviewing the reconstruction photographs at the three flow conditions (i.e., at pressure drops of 50, 100 and 150 psi), the increase in droplet flux may be seen with the corresponding increase in flow rate. Comparison of the various photographs also suggests a finer degree of atomization at the increased flow conditions.

The series of photographs contained in Figure 4-14 shows the reconstruction of a hologram made of the edge view of a test injector element spray fan. In other words, the central plane of the spray fan was perpendicular to the plane of the photographic plate. This hologram was made to give qualitative and preliminary indication of the droplet mass flow which the intense coherent light of the laser could penetrate. Photographs of the reconstructed hologram were made at focal planes of up to 4 centimeters on either side of the reference plane. The arbitrary reference was a plane passing through the axial centerlines of the impinging stream orifices and the stream impingement point. It should also be noted that this hologram was made at a pressure drop of 75 psi across the injector.

Figure 4-14 illustrates the capability of pulsed laser holography to capture a moderately dense droplet spray pattern as represented by the edge view orientation of this spray pattern. Reconstruction photographs (lens setting at f/5) taken at nine different focal planes across the spray fan show distinct droplet dispersions at the respective locations.

After these experiments were completed, it was found that the laser emission was low due to dust attracted to one of the Kerr cell windows by its 19,000 volt quarter wave bias voltage. Cleaning of the window gave shorter duration, higher amplitude pulses. For this reason, additional tests were made since it was anticipated that better quality holograms would be produced. Further, it was desirable to have a calibration device in the test scene so that magnification of the reconstructed holograms could be closely controlled. The results of this second test series are presented in the example illustrations of Figures 4-15 and 4-16.

The photographs in Figures 4-15 and 4-16 are copies of reconstructed holograms 7-26-67-5 and 7-26-67-8. The test element was Princeton injector JP4M-232A. Water was emanating from both like-on-like impinging stream flow passages in the injector. With this element, the resultant flow consists of



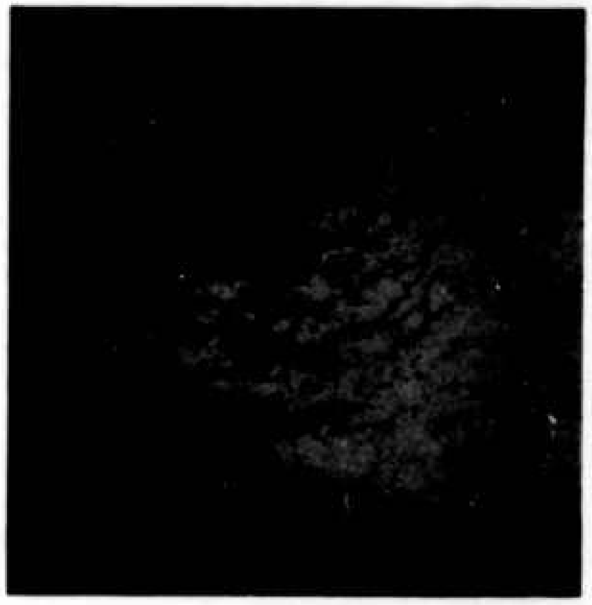
f/5, 0 cm | f/5, +1 cm | f/5, +2 cm | f/5, +3 cm | f/5, +4 cm

f/5, -4 cm | f/5, -3 cm | f/5, -2 cm | f/5, -1 cm | f/16, 0 cm

Figure 4-14. Photographs of the reconstruction of hologram 7-14-67-1, Princeton injector JP4M-242A operating at a pressure drop of 75 lb/in^2. The pictures differ by the location of the fixed focus copy camera relative to the center of the fan, also by the lens setting of the copy camera. In this case the plane of the fan was perpendicular to the plane of the photographic plate.

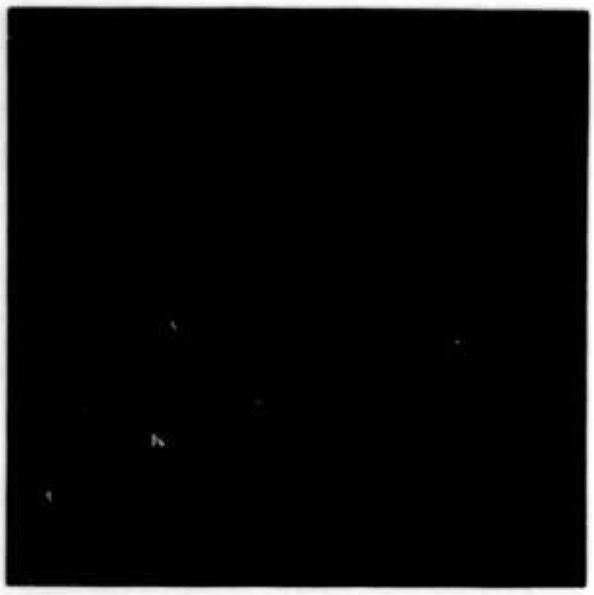
f/5, 0 cm

f/5, -1 cm

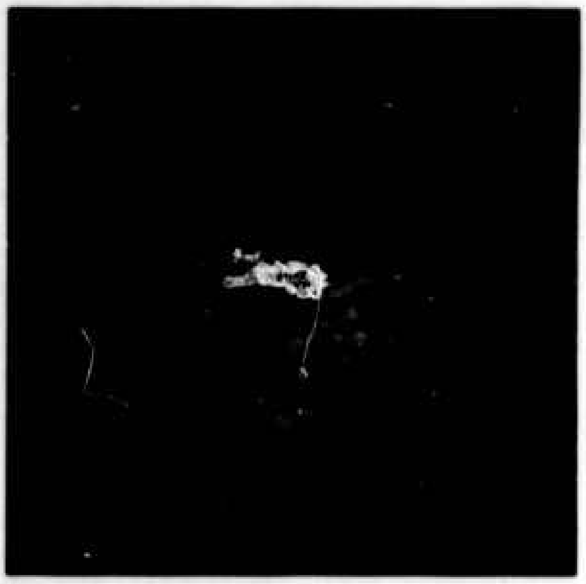


f/5, +1 cm

Figure 4-15. Three photographs of the reconstruction of a ruby laser hologram showing Princeton injector JP4M-232A operating with water at a pressure drop of 50 lb/in^2. Both sides of the injector element were flowing, resulting in two side-by-side spray fans. The pictures differ by the position of the copy camera relative to the two spray fans.



f/5, 0 cm



f/5, -1 cm

f/5, +1 cm

Figure 4-16. Three photographs of the reconstruction of a ruby laser hologram showing Princeton injector JP4M-232A operating with water at a pressure drop of 100 lb/in^2. Both sides of the injector element were flowing, resulting in two side-by-side spray fans. The pictures differ by the position of the copy camera relative to the two spray fans.

two parallel spray fans. The parallel fans are offset — one from the other — approximately 1/8 inch.

The photographs of both Figures (4-15 and 4-16) were recorded on Polaroid Type 55 P/N film at an f/5 lens aperture. The exposure time for each film was 15 seconds. A clear plastic drafting scale (50 divisions to the inch) was added to the original scene to provide a means of calibration during reconstruction. The use of this type of scale turned out to be a poor choice. The beveled edge of the scale refracted light away from the photographic plate. Upon reconstruction, the edge of the scale showed up as a dark band across the bottom of the copy photographs. Aside from this, the quality of the holograms was excellent.

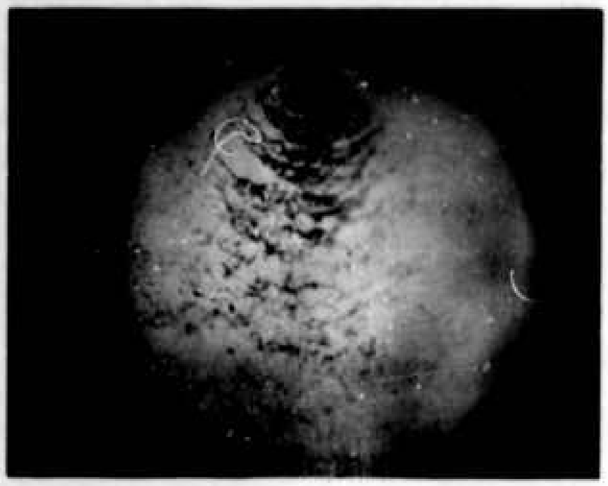
A comparison of the photographs in Figures 4-11 (discussed previously) and 4-16 indicates the more dense droplet flow conditions of the latter figure where both sides of the injector element were flowing. In each case, the elements were operating at a pressure drop of 50 lb/in^2. A similar qualitative comparison may be made between Figures 4-12 and 4-16. In this instance, the injector was operating at a pressure drop of 100 lb/in^2.

Figure 4-17 presents a series of reconstruction photographs of hologram number 8-29-67-1. Only one side of Princeton injector element JP4M-232A is flowing water. The pressure drop across the impinging stream orifices is 50 lb/in^2.

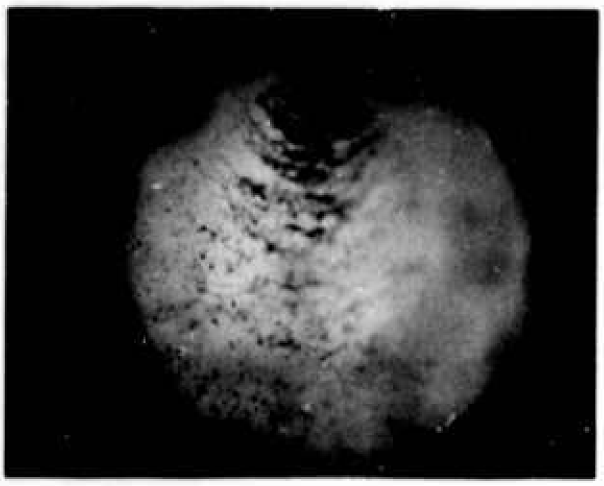
Prior to making the hologram, a clear plastic plate with a scribed calibration grid was placed within the test scene. The grid was composed of 1/2-inch primary divisions. The major x and y axes were subdivided into 10 divisions to the inch. This type of calibrating device proved successful and demonstrates an approach which will be used in the future.

The quality of this particular hologram (8-29-67-1) was excellent. Reconstruction photographs were (arbitrarily) taken at the "zero" reference plane and at focal planes one centimeter on either side of the reference. The fourth picture (in Figure 4-17) was made to bring the calibration grid into sharp focus.

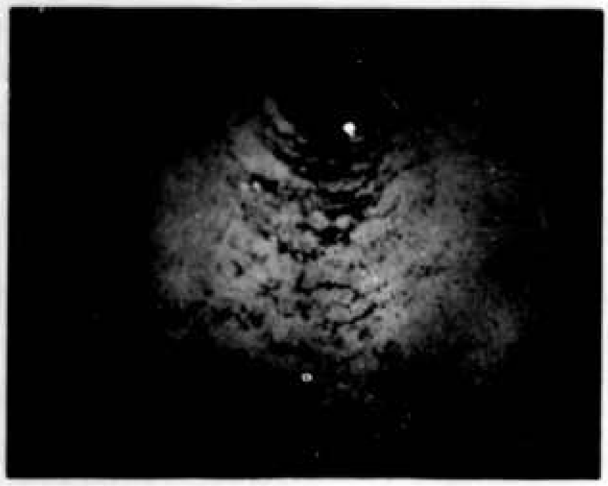
The photograph in Figure 4-18 shows the reconstruction of a hologram made of the water flow characteristics of a significantly larger doublet injector than the Princeton elements previously discussed. This particu-



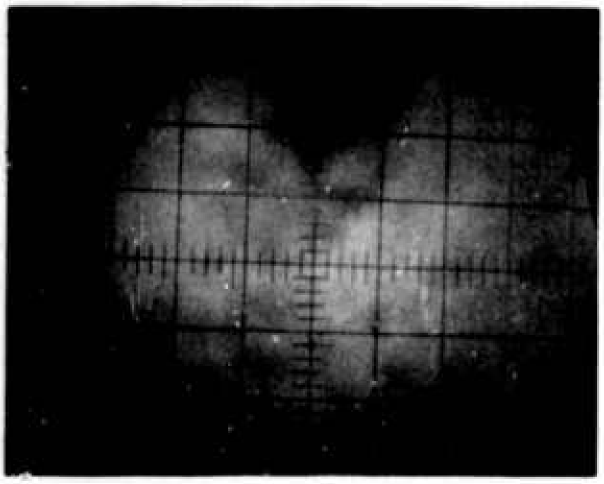
f/5, 0 cm



f/5, -1 cm



f/5, +1 cm



f/5, +7 cm

Figure 4-17. Photographs of the reconstruction of a ruby laser hologram showing Princeton injector operating at a pressure drop of 50 lb/in^2. The pictures differ by the position of the copy camera relative to the single spray fan. A calibration grid was included in the original test scene.

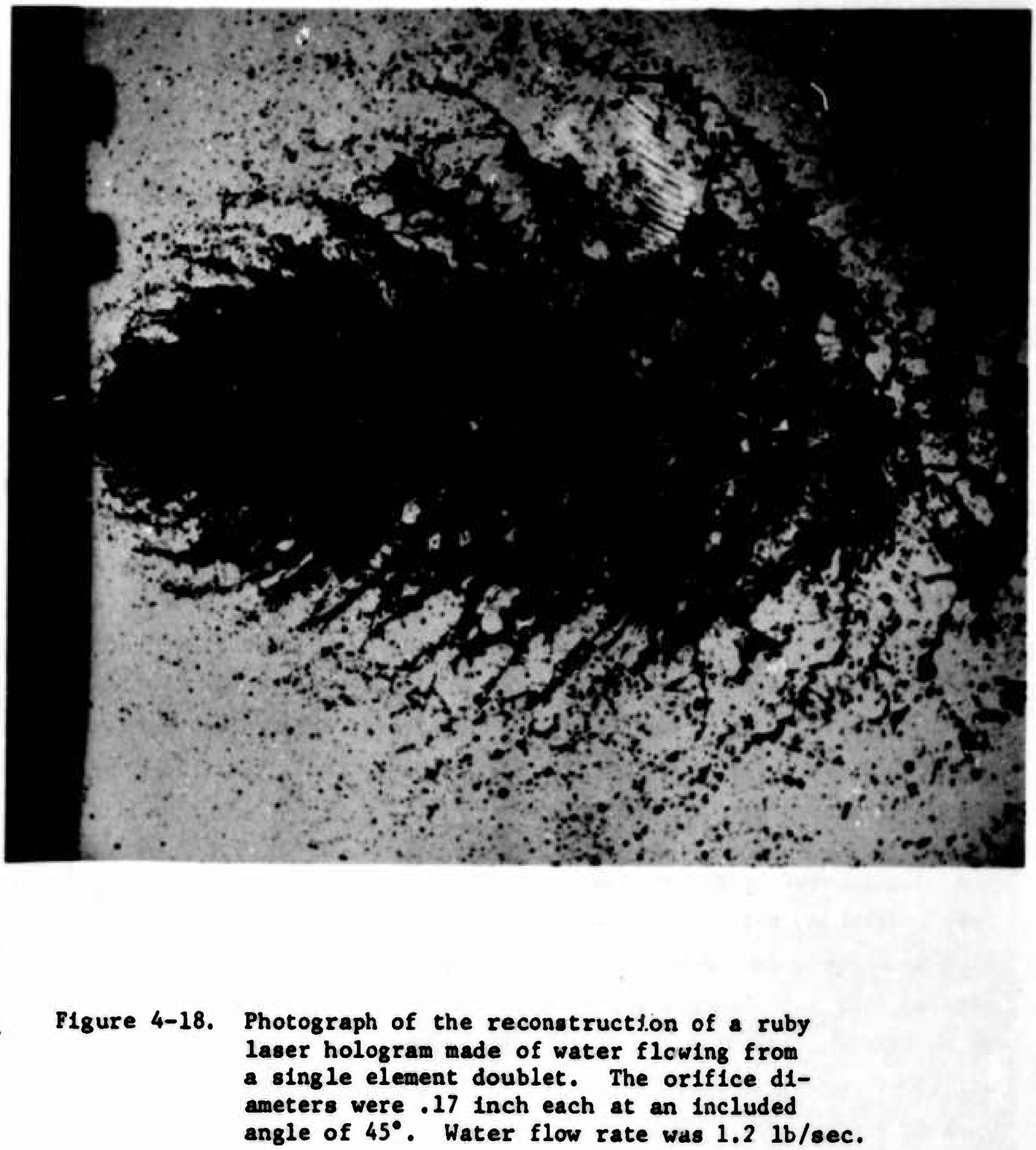


Figure 4-18. Photograph of the reconstruction of a ruby laser hologram made of water flowing from a single element doublet. The orifice diameters were .17 inch each at an included angle of 45°. Water flow rate was 1.2 lb/sec.

lar injector element consists of two .17 inch diameter orifices aligned at an included angle of 45°. The water flow rate (illustrated by the spray fan in Figure 4-18) is approximately 1.2 lb/sec. This is an order of magnitude greater than the nominal flow rate for the Princeton elements.

For the discrimination between fuel and oxidizer simulants flowing in a liquid rocket injector, a laser which emits at more than one wavelength is required. One very potent possibility is the generation of light at twice the frequency of the original laser light by the process of second harmonic generation (Reference 32). This is done by passing the ruby laser output through a crystal whose index of refraction or dielectric constant is proportional to the instantaneous electric field intensity. The net result is the production of light of twice the frequency. One crystal which has been successfully used is potassium dihydrogen phosphate (KDP). When properly originated so that the primary red beam at 0.694 micron travels through the crystal at the same speed as radiation of twice the frequency, the crystal converts approximately 5-10 percent of the initial radiation into radiation of 0.347 micron wavelength. For holographic considerations, the inefficiency of the process is compensated by the fact that photographic films are actually more sensitive in the ultraviolet (UV) region of the spectrum; particularly the plates manufactured by Eastman Kodak Company with their 649F emulsion. These plates have equal darkening or sensitivity for the approximatey 95 percent residual of the 0.694 micron primary radiation as for the 5 percent of the 0.347 micron doubled radiation.

Small Gabor holograms have been made at TRW Systems with doubled ruby radiation, but the work has been on a too sporadic basis for publication as a paper in the scientific literature. In essence, it has been demonstrated that such holograms could in fact be made. This work has not gone as far as to test the simultaneous manufacture of holograms made with both colors of light. It was planned to report on the preliminary accomplishment of such work in the present summary. The technique was to place the doubling crystal just before the entrance aperture of the holocamera shown in Figure 4-7. A Corning filter would be used to block the primary beam, thereby establishing that there was sufficient energy to record a 4x5 inch UV hologram. The hologram would then be reconstructed with the primary 0.48 micron blue line from an ionized argon laser recently constructed at TRW Systems. The satisfactory production of such a hologram would lead to a hologram made simultaneously with the red and doubled radiation. Reconstruction would then be with both ultraviolet and helium-neon lasers. Absorbing blocks would be inserted in the scene to demonstrate the ability to discriminate against ultraviolet opaque materials and vice versa. The time schedule for this work was too brief, and as a result, the tests have not been completed.

4.3 SPARK PHOTOGRAPHIC STUDIES

One of the objectives established for Phase I was the conduct of spark photographic studies at Princeton University which incorporated specific system improvements. The studies were to be conducted to permit direct comparison of this technique with that of pulsed laser holography in the detection of small droplets.

The spark photographic studies have not been completed at this writing. The unavailability of a proper Kerr cell to achieve a 50 nanosecond shuttering of the light pulse precluded the completion of these tests. The Kerr cell which was to have been used for these tests had to be shipped to the vendor (Electro Optical Instruments) for repair. Delays in the repair and return of this unit ultimately forced postponement of the scheduled Phase I spark photographic test program.

The spark photographic equipment to be used for the intended experiments is shown in Figure 4-19. In the work to date, preliminary checkout of the equipment is complete including optical alignment of the components. The water spray element used in making the initial pulsed laser holograms has been returned to Princeton for use in the spark photographic work.

Testing could have been initiated without the Kerr cell; however, to achieve exposure times consistent with making accurate measurements down to the smallest droplet diameters (10 microns) under consideration, a 50 nanosecond light pulse was considered necessary. Spark discharge is normally about 1 microsecond in duration. Spark photographic studies with spark durations of this order have been conducted in the past, and the results are documented (References 10 and 33). For these reasons, it was decided to postpone the spark photographic studies until the Kerr cell could be utilized.

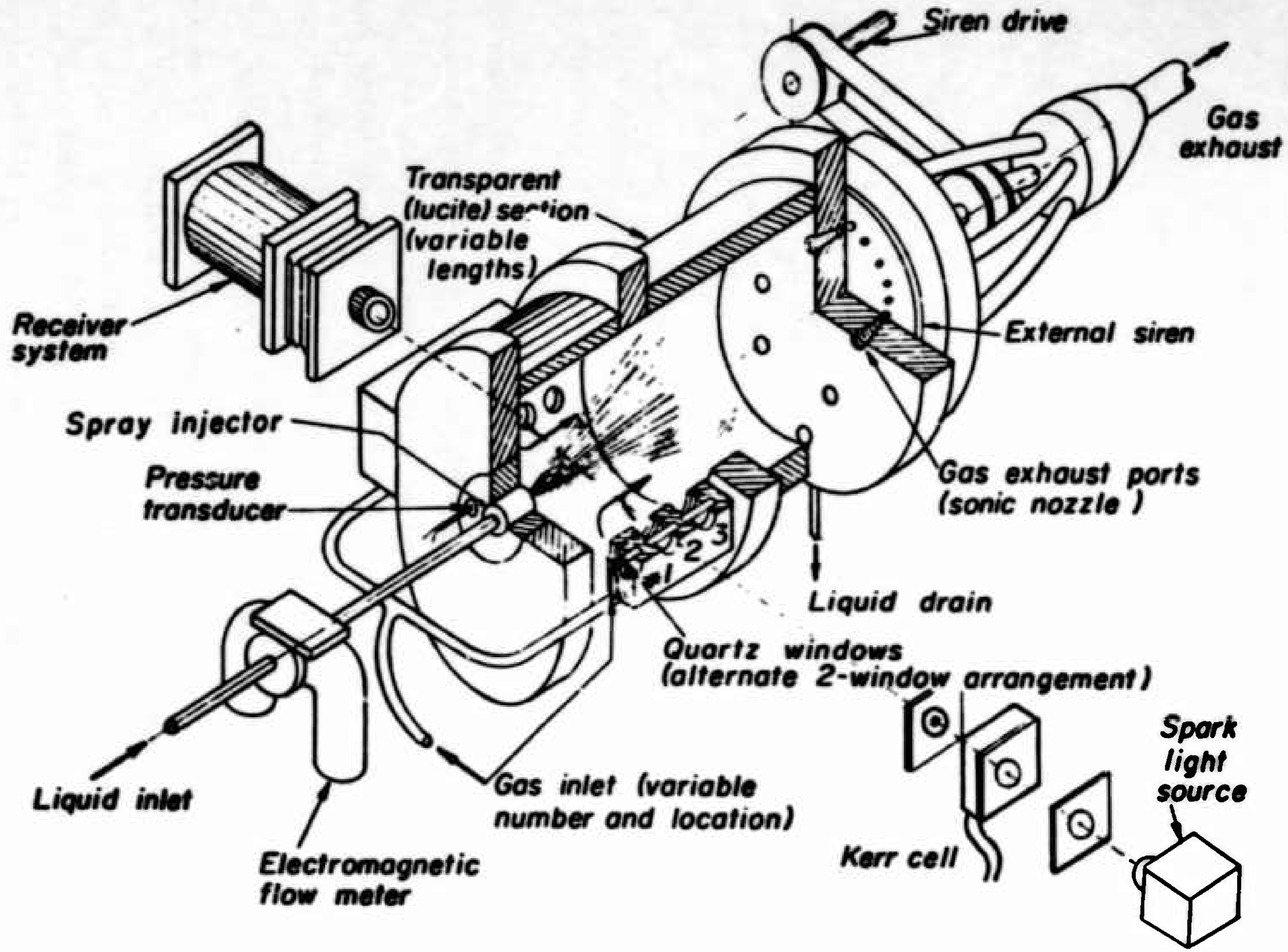


Figure 4-19. Schematic of Princeton University spark photographic test setup showing windowed resonating chamber, spark light source, and light receiving system.

4.4 DATA REDUCTION TECHNIQUE

The achievement of a comparatively rapid and inexpensive data reduction and processing technique is no less important to the study of droplet spray phenomena than the realization of precise droplet detection systems. As a result, considerable effort has been expended toward developing an automated system involving a mechanical scanning device coupled to a suitable computer program. The results of this work, which is being conducted by Princeton University under a subcontract arrangement, are presented in the following text.

4.4.1 Mechanical Scanning Device

In the coupling of a scanning device (electrical or mechanical) to a computer, it is necessary to understand that computers have a finite memory capacity. Conversely, the output of nearly any scanning device approaches infinity for long scanning times. The automatic analysis of photographic records of droplet sprays must, therefore, be concerned with both the scanning mechanism and the computer program.

The basic philosophy of the computer program is to record only droplets and not blank film areas. In addition, there is always a problem of matching scan records to determine the size of a droplet. The time required to compute a matching base index should be kept small. This leads to a device which will record several adjacent scans within one record in the computer. In the current program. 20 scans per second was chosen for convenient operation.

A mechanical scanner (Figures 4-20 and 4-21) has been built to provide a means of traversing a film record in a spiral manner (similar to telegraph facsimile transmission). The Particle Analyzer and Traversing Mechanism can move an oriented bundle of 20 glass fibers, each of 10 micron diameter, in a spiral band in the axial direction. The movement is such that the first fiber records information adjacent to the last fiber on the previous revolution of the film drum. A precision screw and antibacklash gears are used to accomplish this traverse. An assembly drawing of the scanning device is illustrated in Figure 4-22.

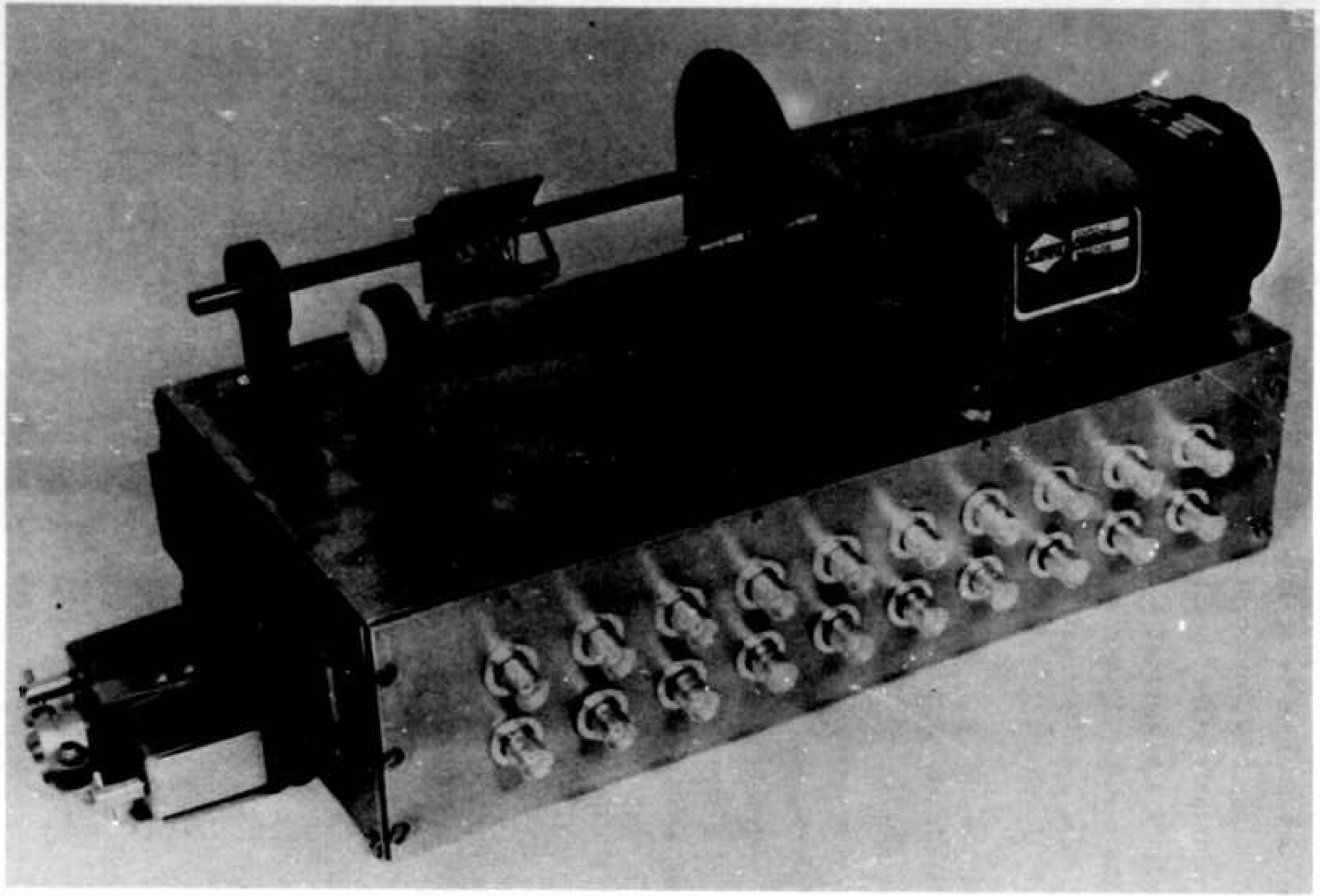


Figure 4-20. Rear view of Princeton University Particle Analyzer and Traversing Mechanism Assembly showing fiber optic array holder mounted on lead screw parallel to quartz cylinder around which the film record is wrapped.

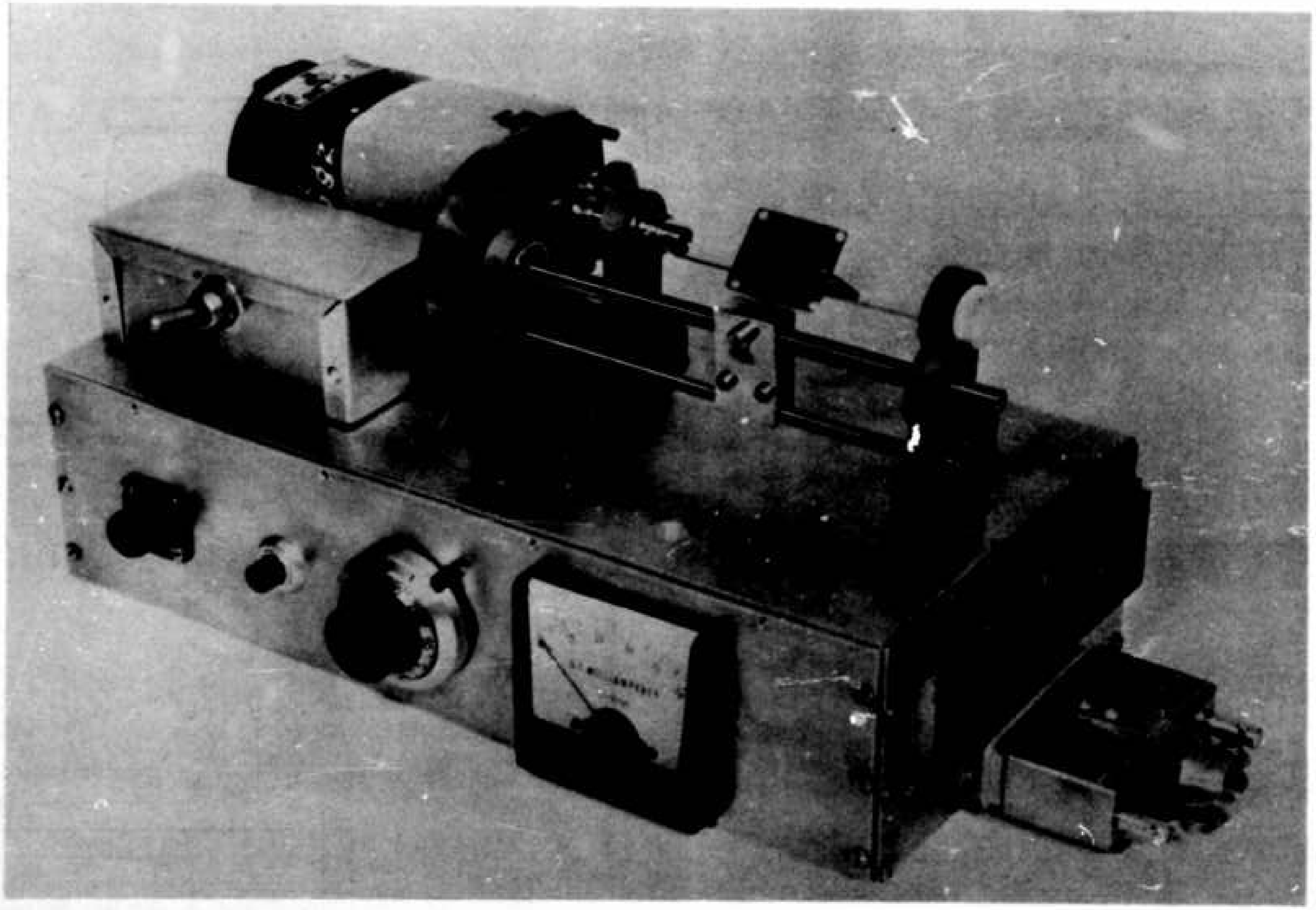


Figure 4-21. Front view of Particle Analyzer and Traversing Mechanism Assembly showing the lead screw sub-assembly.

GEAR TRAIN	P.D.	O.D.	RPM	TEETH
MOTOR	.8333	.875	.250	40
DRUM	.6042	.646	.344	29
LEAD	2.7500		.076	132

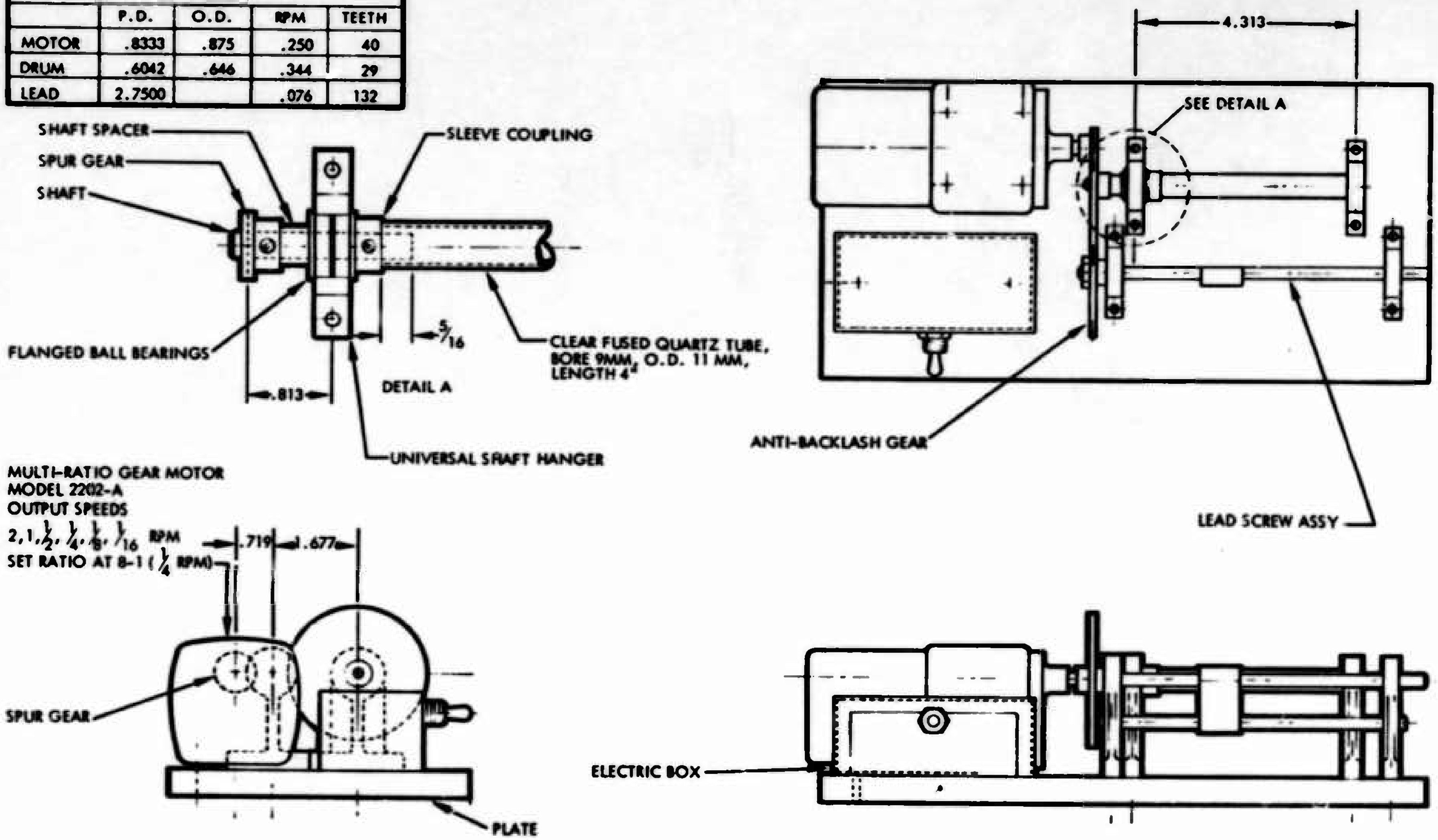


Figure 4-22. Assembly drawing of Princeton University Particle Analyzer and Traversing Mechanism.

The optics associated with the mechanism are:

- Light-emitting diodes
- Film record of droplets
- Glass fibers
- Light-sensing diodes

The light-emitting diodes, glass fibers, and light-sensing diodes are mounted on the precision screw and therefore may be expected to remain in alignment. The voltage output of the light-sensing diodes is then digitized and entered into a computer, in this case, an IBM 1620 computer with special modifications to allow the entry of such external digital information.

The specific components of the Traverse Mechanism are as follows:

- Multi-ratio motor - Bodine 2202-2
- Fiber optics array - 20 fibers, 10 microns each
- Light sensors - Texas Instruments LS 600
- Light-emitting diode - Texas Instruments XL 01
- Quartz tube to mount film
- Lead screw assembly
- Gear train

Each light sensor has its own output potentiometer for compensation of different sensitivities to match all 20 channels so that the computer does not have to make the scale adjustments at a later time.

To scan a film, the negative is mounted on the quartz drum with a fiducial mark to denote the rotation position. The light-emitting diodes and scanner head are adjusted to the initial position. The computer and scanner motor are then started, not necessarily even at the same time since the fiducial mark will cause an automatic start of the computer recording program.

Two design criteria were used based upon present equipment. These are: 1) The sampling rate which is limited to 400 samples per second (i.e., 20 samples/sec from each fiber) by the existing analog-to-digital converter; and, 2) A 200 micron width of observation (20 fibers of 10 micron each).

The following set of specifications were then computed for 35 mm film:

- Drum speed = 0.344 rpm
- 127 drum revolutions per negative
- Motor speed = 0.25 rpm
- Lead screw = 0.0357" or 906.78 micron/rev
- Lead screw = 0.076 rpm
- 28.01 lead screw revolutions per negative
- Sampling time for a 35 mm negative = 6.2 hr
- 8.9×10^6 samples per negative (each sample = 100 square microns)

The slowest component in this system is the 400 sample/second analog-to-digital converter. This is being used only as a feasibility study apparatus. There are new analog-to-digital converters available to operate at speeds several orders of magnitude above this. A factor of 20 increase in speed would reduce the scanning time to about 18 minutes, even on the IBM 1620 computer. Newer computers can accept data at even higher rates and can also be performing the data reduction at the same time through the use of Input/Output (I/O) channels.

The most difficult aspect associated with the scanner mechanism concerns the fabrication of the 20 carefully oriented glass fibers. Several different methods have been attempted. One approach used hypodermic tubing (0.006-inch diameter) as a conduit to protect the fragile glass fiber elements. A difficulty associated with that approach was that atmospheric dust would clog some of the tube openings or interfere with the final arrangement of the elements.

It appears now that the best mounting technique bypasses the conduits. Instead, assembly is begun by laying the fibers side-by-side and bonding them together at the "film end". Then five elements are separated at a time and are threaded through the sensor board until the four rows are completed. Based on the experience gained from the early partial assemblies, it is anticipated that the present technique will yield an easily handled assembly. Following satisfactory assembly, the fiber array will be calibrated by use of Moire patterns and a grating replica.

The processing of this stored information is done by reading back into the memory the four sets of 20 scans and making several decisions at the time. An increase of more than one time unit in the time of scan indicates that the previous droplet has ended. Then, three classes of droplet positions must be determined. It follows that (in the scanning process) the droplet could run into the right edge of the scan, the left edge of the scan, or be entirely contained within the 20 samples. Obviously, the last case is easiest to solve and is done in a very simple manner. The diameter is computed from an area by an approximation (with less than a 2 percent error) termed the equivalent diameter. The equivalent diameter = $\sqrt{\frac{4A}{\pi}}$ where A = 11 x sum of intensities.* If π is approximated as 22/7, then the equivalent diameter is $D = \sqrt{14 \times \text{sum of intensities}}$. The square root is done as an approximation plus one iteration by Newton's method. This is very fast and only requires a small fraction of the total computing time.

If a droplet image extends beyond the right side of the 20 fibers, then some information about that image must be stored for use in the next scan analysis. The information necessary is the current sum of intensities, current diameter, the time value at the center, and a special parameter for record destruction as diameters are determined. If a droplet image extends to the left of the first fiber and terminates in the 20 scans, analysis of stored data from previous scans is done.

To date, a set of cards with simulated droplet data has been generated for the purpose of checking the computer program. Checks have been run with this system and have been successful. The program, incidently, is currently written in FORTRAN which will probably be too slow for production analysis. The FORTRAN may be easily converted to 1620 machine language for increased speed and capacity.

4.4.2 Computer Analysis

The computer analysis is accomplished in two steps, which are recording and then analysis. The IBM 1620 computer has a disk file (1311) for ex-

* Storage in the computer is on a 0-9 light intensity gradation scale so that droplets out of focus (and hence gray on the negative) can be eliminated in the resulting analysis.

ternal storage of data. This disk file can hold 2×10^6 digits or approximately 25 percent of the total number of samples on a 35 mm film. However, since we are only storing non-blank film areas, the 2×10^6 digits are more than adequate for recording an entire 35 mm frame. The record format on the disk requires that four scans of all 20 fibers be accumulated before one record is written onto the disk. Associated with each scan of 20 fibers is a time (equivalent to position) which is used to identify the x-y coordinates of the scan.

5. CONCLUSIONS

Of the various techniques evaluated, the application of pulsed laser holography to small droplet detection appears to offer the most promise of ultimately meeting program objectives. The feasibility of using this technique to record cold flow droplet dispersions was demonstrated during the Phase I test program. Further, it is realistic to assume that pulsed laser holography is potentially applicable to rocket engine combustion studies.

The limitations associated with laser holography in precisely resolving very small droplets in a dynamic event, or in making such measurements in extremely high droplet flux levels remain to be determined experimentally. There are some indications in the literature that 10 micron resolution is entirely possible. Published results, however, cannot be totally related to the requirements and objectives of this program. For this reason, additional test work is required to establish ultimate resolution of static and dynamic particles or droplets.

The capability of determining mixture ratio distributions present in a cold flow spray, using holographic techniques, appears possible. A preliminary study has indicated potential; however, it must be reduced to a practical state before evaluation is made.

Of the other six droplet detection techniques considered, all but one was concluded to be unacceptable when evaluated against the program objectives. Primarily, the various methods were found to: 1) not be capable of resolving droplets down to the 10 micron size range; 2) not be applicable to the hot firing situation (considered very important); and, 3) be too restrictive in the method of conducting the test or in the propellant simulants utilized, to be of practical importance for this program.

The single exception to the above comments is the employment of an improved spark photographic technique. Spark photographic methods have been successfully used in previous droplet studies. With improvements in the spark intensity, this technique may be considered an alternate to pulsed laser holography. Since the method employs conventional photography (whether the light source is produced by a spark discharge or a laser), prior selection of a point or a plane of interest within the event under study is required. It does not have the inherent capability of holographic methods which record the three-dimensional features of an event taking place within a scene-volume. In this respect, spark or laser illuminated photography does not have the versatility of pulsed laser holography.

The task of economically reducing large quantities of droplet data is considered equally as important as that of initial data acquisition. Further, the data reduction system should be compatible with the primary drop detection method if the entire process is to be automated. After a review of the literature, it was concluded that the Particle Analyzer concept being developed by Princeton University offers the most potential of satisfying the objectives of this program.

The other methods available were either not compatible with holographic or photographic techniques, or did not provide the desired speed or the required accuracy in the small droplet size range (to 10 micron diameters). The Particle Analyzer system will be capable of accurately measuring 10 micron droplets recorded on a 35 mm film record. Ultimately, the use of suitable analog-to-digital conversion equipment will allow the scanning of a complete 35 mm film in 18 minutes or less.

6. PHASE II OUTLINE

The following outline is submitted as a fulfillment of the requirement of Appendix "B" to Exhibit "B" of Contract F04611-67-C-0105. The outline shows, for consideration, a series of tasks to be accomplished during Phase II of the Small Droplet Measuring Technique Program. The outline of work suggested for Phase II is to be considered as preliminary. Final definition of the tasks will be presented in the Phase II Program Plan.

I. <u>Pulsed Laser Holography Studies</u>

   A. Determine limits of droplet size resolution

      1. Establish calibration procedure
      2. Establish standard test conditions

   B. Demonstrate capability to measure droplets at various locations

      1. At any point across a 6-inch diameter injector
      2. At any point axially from the injector face onward

   C. Investigate feasibility of distinguishing local mixture ratio conditions

   D. Determine droplet flux level limitations with regard to detecting and measuring individual droplets

   E. Investigate and compare several types of injector elements at various operating conditions

II. <u>Improved Spark Photographic Studies</u>

   A. Determine limits of droplet size resolution

   B. Investigate droplet flux level limitations with regard to detecting and measuring individual droplets

III. <u>Data Reduction Studies</u>

   A. Continue buildup of particle analyzer and traversing mechanism

   B. Demonstrate feasibility of computer-based, fiber optics data reduction technique

      1. Conduct calibrations
      2. Reduce samples of hologram reconstruction pictures
      3. Reduce samples of spark photographic studies

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13. ABSTRACT A study and experimental program is being conducted which involves the detection and analysis of size distributions of droplets associated with the injection process in liquid propellant rocket engines. Program objectives are to: (1) Determine, through a review of the literature, applicable methods of detecting and recording rocket injector droplet spray distributions; (2) Demonstrate feasibility of experimental techniques selected from the literature using cold flow propellant simulants; and, (3) Improve the methods of data reduction such that large quantities of droplet data may be reduced economically.

The program is divided into two phases. Phase I is primarily devoted to a review of the literature for applicable spray measuring and data reduction techniques. A limited amount of experimentation is included in this phase to assist in the evaluation of the various techniques and methods under consideration. Phase II is concerned with the design, assembly and feasibility demonstration of the droplet detection techniques selected as a result of the Phase I effort. Development of a compatible droplet data reduction method will comprise an integral portion of the second phase effort.

This report reviews the Phase I activities during the period 1 May through 30 August 1967. Candidate droplet detection techniques and data reduction methods are discussed in context with program objectives and evaluation criteria. Particular attention is given to the application of holography to droplet detection and the results of preliminary holographic experiments are indicated. Conclusions are presented based upon the results of the literature review and the Phase I experimentation. A program plan for the second phase is outlined.

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